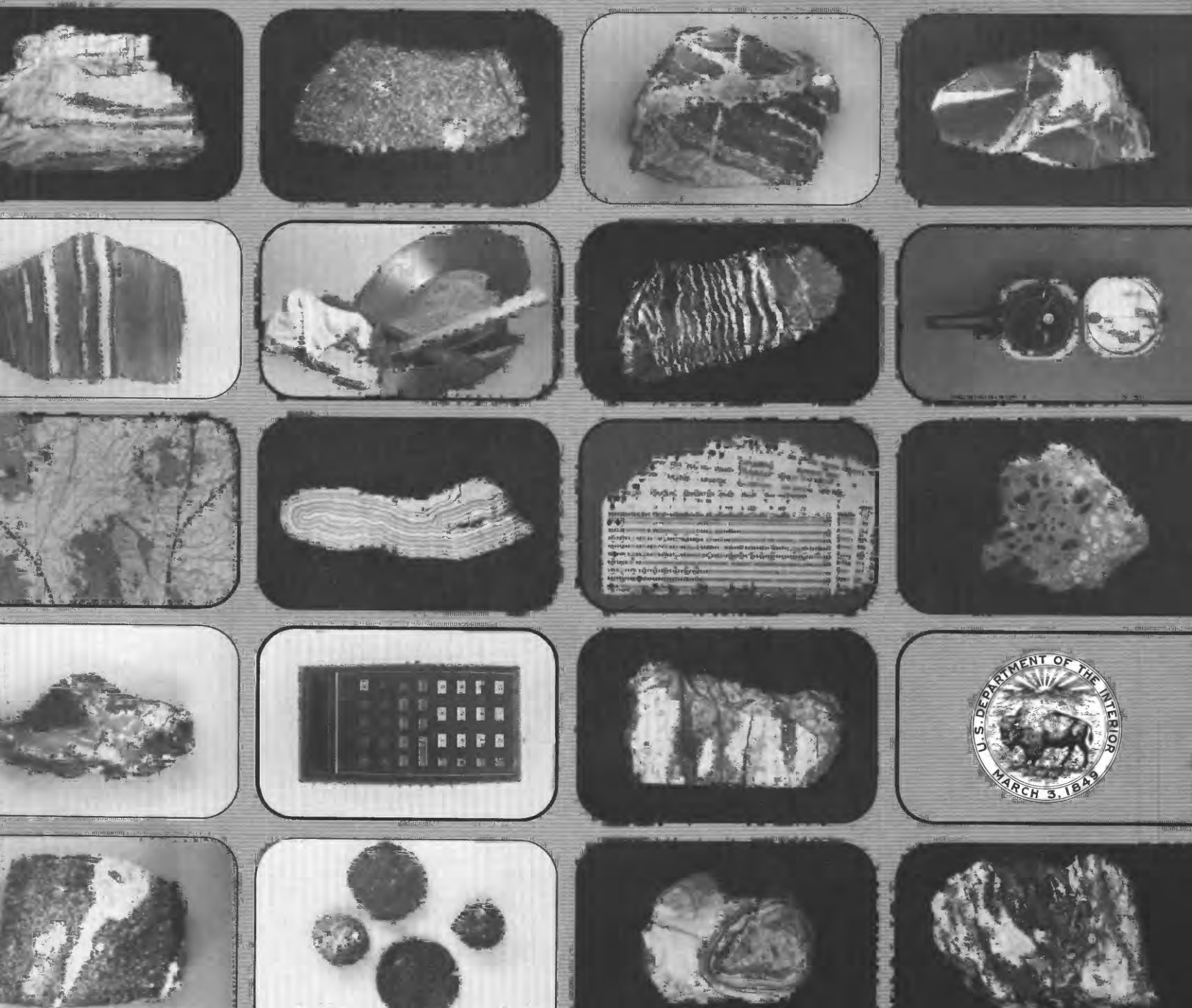


# Geology and Resources of Thorium and Associated Elements in the Wet Mountains Area, Fremont and Custer Counties, Colorado

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-F



COVER PHOTOGRAPHS

1	2	3	4
5		6	
	7		8
9		10	
11	12	13	14

1. Asbestos ore

2. Lead ore, Balmat mine, N. Y.

3. Chromite-chromium ore, Washington

4. Zinc ore, Friedensville, Pa.

5. Banded iron-formation, Palmer, Mich.

6. Ribbon asbestos ore, Quebec, Canada

7. Manganese ore, banded rhodochrosite
8. Aluminum ore, bauxite, Georgia

9. Native copper ore, Keweenawan Peninsula, Mich.

10. Porphyry molybdenum ore, Colorado

11. Zinc ore, Edwards, N. Y.

12. Manganese nodules, ocean floor

13. Botryoidal fluorite ore, Poncha Springs, Colo.

14. Tungsten ore, North Carolina

# Geology and Resources of Thorium and Associated Elements in the Wet Mountains Area, Fremont and Custer Counties, Colorado

By THEODORE J. ARMBRUSTMACHER

GEOLOGY AND RESOURCES OF THORIUM IN THE UNITED STATES

---

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-F

*A description of the geologic setting, mineralogy, geochemistry, and size of thorium and rare-earth deposits, including calculations of reserves and potential economic resources*



DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

---

Library of Congress Cataloging-in-Publication Data

Armbrustmacher, Theodore J., 1946-

Geology and resources of thorium and associated elements in the Wet Mountains area, Fremont and Custer Counties, Colorado.

(Geology and resources of thorium in the United States) (U.S. Geological Survey professional paper ; 1049-F)

Bibliography: p.

Supt. of Docs. no.: I 19.16:1049-F

1. Thorium ores—Colorado—Wet Mountains Region. 2. Earths, Rare—Colorado—Wet Mountains Region. 3. Geology—Colorado—Wet Mountains Region. 4. Mines and mineral resources—Colorado—Wet Mountains Region. I. Title. II. Series. III. Series: Geological Survey professional paper ; 1049-F.

QE390.2.T45A76 1988

553.4'93

87-600023

---

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,  
Federal Center, Box 25425, Denver, CO 80225

## CONTENTS

	Page		Page
Abstract .....	F1	Thorium deposits—Continued	
Introduction .....	1	Carbonatites—Continued	
Location and access .....	1	Selected carbonatite occurrences—Continued	
Previous work and prospecting history .....	2	McClure Gulch carbonatite .....	F10
Present investigation .....	2	Gem Park carbonatites .....	12
Acknowledgments .....	3	Isotopic ratios .....	14
Geologic setting .....	3	Red syenite dikes .....	17
Proterozoic metamorphic rocks .....	3	Mineralogy .....	18
Early and Middle Proterozoic granitic rocks .....	3	Geochemistry .....	19
Cambrian alkaline intrusive complexes .....	4	Quartz-barite-thorite veins and fracture zones .....	20
Fenite .....	4	Mineralogy .....	20
Tertiary volcanogenic rocks and Quaternary sediments .....	6	Geochemistry .....	22
Thorium deposits .....	6	Selected vein-fracture zone occurrences .....	23
Carbonatites .....	6	Haputa Ranch area .....	23
Replacement carbonatites .....	6	Tuttle (or Lepley) Ranch area .....	25
Mineralogy .....	7	Beardsley deposit .....	27
Geochemistry .....	7	Schwarz Ranch claims .....	28
Primary magmatic carbonatites .....	7	General Ike vein .....	28
Mineralogy .....	7	Resources of thorium and other elements .....	30
Geochemistry .....	10	Veins and fracture zones .....	32
Selected carbonatite occurrences .....	10	Carbonatite dikes .....	32
Goldie carbonatite .....	10	References cited .....	33
Amethyst carbonatite .....	10		

## ILLUSTRATIONS

		Page
PLATE	1. Geologic map and sample localities of thorium deposits in the Wet Mountains area, Colorado .....	In pocket
FIGURE	1. Index map of Colorado showing location of area in plate 1 .....	F2
	2. Plot of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data from table 9 .....	17
	3-6. Geologic map and sample localities of thorium deposits:	
	3. Haputa Ranch area .....	24
	4. Tuttle (Lepley) Ranch area .....	26
	5. Beardsley deposit .....	29
	6. Schwarz Ranch claims .....	30

## TABLES

---

	Page
TABLE 1. Chemical analyses of "r" granite .....	F5
2. Mineralogy of Wet Mountains carbonatites .....	8
3. Arithmetic means and ranges of elements in Wet Mountains carbonatites .....	9
4. Mineralogy of carbonatites from McClure Gulch .....	11
5. Chemical analyses of carbonatites from McClure Gulch .....	13
6. Mineralogy of carbonatites in diamond drill core from Gem Park .....	14
7. Modal analyses of 29 carbonatites in diamond drill cores from Gem Park .....	15
8. Summary of geochemical data from carbonatites in diamond drill core from Gem Park .....	16
9. Oxygen and carbon isotopic compositions of carbonatites from the Wet Mountains area .....	17
10. Minerals in red syenite dikes .....	19
11. Arithmetic means and ranges of 46 analyses of rocks from red syenite dikes .....	20
12. Mineralogy of quartz-barite-thorite veins and fracture zones .....	21
13. Arithmetic means and ranges of elements from quartz-barite-thorite veins and fracture zones .....	23
14. Abundance of selected elements in fracture zones from the Haputa Ranch area .....	25
15. Abundance of selected elements in veins and fracture zones from the Tuttle (Lepley) Ranch area .....	27
16. Abundance of selected elements in one sample of material from the Beardsley deposit .....	30
17. Abundance of selected elements in veins and fracture zones from the Schwarz Ranch claims .....	31
18. Abundance of selected elements in veins and fracture zones from the General Ike vein .....	32

## GEOLOGY AND RESOURCES OF THORIUM AND ASSOCIATED ELEMENTS IN THE WET MOUNTAINS AREA, FREMONT AND CUSTER COUNTIES, COLORADO

By THEODORE J. ARMBRUSTMACHER

### ABSTRACT

Thorium in potentially economic amounts occurs in three types of deposits in the Wet Mountains area of Colorado: (1) quartz-barite-thorite veins and fracture zones, (2) carbonatite dikes, and (3) red syenite dikes. The quartz-barite-thorite veins and fracture zones contain the largest resources of thorium; they cut all Precambrian and Paleozoic rock types in the area and tend to strike normal to the foliation in the Proterozoic metasedimentary and metavolcanic rocks. The veins and fracture zones are end products of the episode of Cambrian alkaline magmatism that also produced rocks of the McClure Mountain Complex, the Gem Park Complex, the complex at Democrat Creek, and associated dikes of carbonatite, lamprophyre, and red syenite. The veins and fracture zones contain an average of 0.46 percent  $\text{ThO}_2$ , 0.21 percent  $\Sigma\text{LREE}$  (total light rare-earth elements), 0.14 percent  $\Sigma\text{HREE}$  (total heavy rare-earth elements), and 0.012 percent  $\text{Nb}_2\text{O}_5$ . They contain reserves of 64,200 tons  $\text{ThO}_2$ , 29,300 tons  $\Sigma\text{LREE}$ , 19,540 tons  $\Sigma\text{HREE}$ , 1,675 tons  $\text{Nb}_2\text{O}_5$ ; they contain probable potential resources of 160,500 tons  $\text{ThO}_2$ , 73,270 tons  $\Sigma\text{LREE}$ , 48,850 tons  $\Sigma\text{HREE}$ , and 4,185 tons  $\text{Nb}_2\text{O}_5$ .

The carbonatite dikes form two distinct groups: replacement carbonatites and primary magmatic carbonatites. The latter group appears to be the better source of potentially economic commodities. The primary magmatic carbonatites contain an average of 0.17 percent  $\text{ThO}_2$ , 0.0097 percent  $\text{Nb}_2\text{O}_5$ , 0.0031 percent  $\text{U}_3\text{O}_8$ , and 2.15 percent total rare-earth oxides. The seven largest dikes contain reserves of 131 tons  $\text{ThO}_2$ , 40 tons  $\text{Nb}_2\text{O}_5$ , 17 tons  $\text{U}_3\text{O}_8$ , and 2,500 tons  $\Sigma\text{RE}_2\text{O}_3$  (total rare-earth oxides), and probable potential resources of 753 tons  $\text{ThO}_2$ , 228 tons  $\text{Nb}_2\text{O}_5$ , 105 tons  $\text{U}_3\text{O}_8$ , and 14,300 tons  $\Sigma\text{RE}_2\text{O}_3$ .

The red syenite dikes contain anomalous amounts of thorium, uranium, niobium, and rare-earth elements. Although reserves and probable potential resources have not been calculated, they are likely to be small.

### INTRODUCTION

This paper discusses the mineralogy, geochemistry, and resources of the thorium and rare-earth deposits in the Wet Mountains area of south-central Colorado (fig. 1). Anomalous amounts of thorium and related elements are found in three types of deposits: quartz-barite-thorite veins and fracture zones, carbonatite dikes, and red syenite dikes. These deposits are genetically and

spatially related to three alkaline intrusive complexes of early Paleozoic age that intrude the Middle Proterozoic igneous and metasedimentary host rock. After discovery of these radioactive deposits in the late 1940's, a flurry of prospecting took place in the mid-1950's; minor amounts of hand-cobbed ore from several veins were shipped to several small mills, mainly for testing. Because of the lack of a thorium market, only minor exploration has been done in recent years. However, interest in the economic potential of rare-earth elements and niobium in the carbonatite dikes continues to the present.

### LOCATION AND ACCESS

Thorium deposits occur in an area bounded roughly by the Arkansas River on the north, the Custer-Huerfano County line on the south, the Texas Creek-Westcliffe fault on the west, and the Ilse fault on the east (pl. 1). The area containing the thorium deposits is referred to as the Wet Mountains in earlier literature. Many of the deposits are actually found in an area referred to as the DeWeese Plateau by Scott and Taylor (1975, p. 2); the actual Wet Mountains are east of the Ilse fault (pl. 1). The area is located about 65 km west of Pueblo, Colo., in Fremont and Custer Counties. The communities of Westcliffe and Silver Cliff are near the west-central edge of the area. The magnificent Sangre de Cristo Range is immediately west of the Wet Mountain Valley to the west and provides a scenic backdrop for studies in the area.

U.S. Highway 50 follows the Arkansas River along the northern edge of the area. State Highway 69 follows the western edge of the area south from Texas Creek at U.S. 50 through Westcliffe. State Highway 96 transects the area in an east-west direction from Westcliffe and Silver Cliff east to McKenzie Junction and past the intersection with Highway 165, to Wetmore and Pueblo.

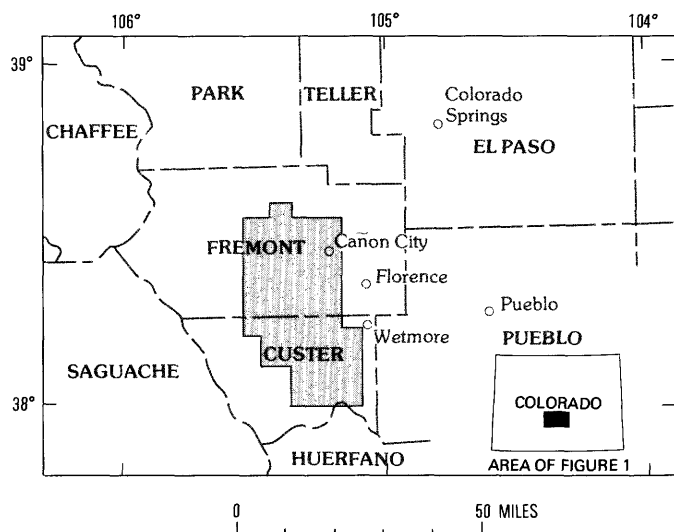


FIGURE 1.—Index map showing location of area in plate 1 (patterned area).

Numerous county roads connect the defunct mining communities of Ilse, Querida, and Rosita with the State highways. Land development in recent years has also provided additional roads throughout the area so that access for the most part is excellent.

Grape Creek, which heads in the Sangre de Cristo Range and flows into DeWeese Reservoir, has cut a canyon diagonally across the DeWeese Plateau that causes some access problems. From DeWeese Reservoir north-eastward toward Temple Canyon, vehicles can ford Grape Creek only at Bear Gulch and then only at times of low water.

#### PREVIOUS WORK AND PROSPECTING HISTORY

Although the geology and mineral deposits of the Wet Mountains area have been known since 1896 (Cross, 1896; Emmons, 1896), thorium deposits were probably first mentioned in 1951 by Dellwig, G.B. Gott and L.F. Dellwig of the U.S. Geological Survey discovered radioactive shear zones at the Haputa Ranch in 1950 using a car-mounted geiger counter while en route to investigate the source of radioactive samples submitted to the Survey by Lawrence C. Knobbe of Silver Cliff (Christman and others, 1953).

Knobbe's interest in radioactive deposits dates from the mid-1940's, and his recollection of events leading to the discovery of thorium in the Wet Mountains area is interesting. During the mid- to late-1940's, various truck crops, particularly potatoes, were grown in the Wet Mountains area. Upon harvesting, the potatoes were sold to wholesalers in nearby Westcliffe and

trucked to various markets by Lee Jones, a local rancher. One sack of potatoes found its way to Knobbe's home in Spearville, Kans., where it was stored in his basement near some rock samples that he had collected. In checking his rock samples for radioactivity, Knobbe discovered that the potatoes were radioactive. Knobbe traced the radioactivity to the bright-red dirt in the eyes of the potatoes, reconstructed the route traveled by the potatoes, and moved to the Wet Mountains area in order to prospect for the radioactive material, which he assumed to be uranium. After submitting samples from the Haputa Ranch, Lee Jones Ranch, and Anna Lee prospect to the Atomic Energy Commission for analysis in 1946-47, Knobbe learned that the radioactivity was due to thorium rather than uranium.

In response to Knobbe's discoveries, the U.S. Bureau of Mines drilled the veins and fracture zones at the Haputa Ranch in 1951-52 (Christman and others, 1953). The U.S. Geological Survey mapped various prospects and the surrounding Precambrian rocks in the vicinity of McKinley Mountain (Christman and others, 1954; Singewald and others, 1955; Singewald and Brock, 1956; and Christman and others, 1959).

Parker and Hildebrand (1963) first reported on the alkaline rock complexes in the Wet Mountains and their associated thorium, niobium, and rare-earth elements. Detailed studies of the alkaline complexes have been made by Shawe and Parker (1967), Parker and Sharp (1970), Armbrustmacher, Hedge, and Parker (1979), and Armbrustmacher and Hedge (1982). Various aspects of the geology of the alkaline rocks have also been studied by Armbrustmacher (1984), Heinrich (1965, 1977), Heinrich and Anderson (1965), Heinrich and Dahlem (1966, 1969), Heinrich and Moore (1970), Heinrich and Quon (1963), and Heinrich and Shappirio (1966).

The study of the thorium deposits has benefited from the areal geologic mapping previously done in the area by the U.S. Geological Survey, especially in the Mount Tyndall 7½-minute quadrangle (Brock and Singewald, 1968), the Cotopaxi and Royal Gorge 15-minute quadrangles (Taylor and others, 1975a, b), the Deer Peak-Hardscrabble Mountain quadrangle (Taylor, R. B., 1974), and the Pueblo 1°×2° quadrangle (Scott and others, 1976).

#### PRESENT INVESTIGATION

This study of thorium deposits in the Wet Mountains area systematically examines their mineralogy and geochemistry. Grab samples weighing about 1,000 grams were collected and ground to -20 mesh. Approximately 250 grams were split from the sample and reground to -100 mesh to prepare them for 6-step



semiquantitative spectrographic analyses for 61 elements. The remainder of the -20 mesh fraction was analyzed for radium-equivalent uranium, thorium, and potassium by gamma-ray spectrometer. After analysis, this same fraction was subjected to routine heavy-liquid and isodynamic magnetic separation and the resulting mineral separates were identified optically or by standard X-ray powder diffraction methods. Many of the samples were also examined petrographically.

In the field, detailed sketch maps were prepared of some of the larger deposits. Radiometric surveys with a hand-held gamma-ray spectrometer and scintillation counter were also used to delineate zones of high radioactivity.

Light stable-isotope studies of carbonatites and veins aided in delineating the physical-chemical conditions of formation of these rocks. R.O. Rye determined  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  contents; this allowed unique solutions to problems of origin of various carbonatites. Determination by Rye of  $\delta^{18}\text{O}$  and  $\delta^{34}\text{S}$  values in quartz and coexisting barite and galena, respectively, also placed constraints on the characteristics of the hydrothermal fluids that deposited the vein materials. Rubidium and strontium isotopic analyses of some of the alkaline rocks indicate a relationship between the intrusions and associated carbonatites and red syenite dikes, and suggest a possible origin of these rocks.

Calculations of thorium, rare-earth elements, niobium, and uranium resources reported in Staatz and others (1979) and in Staatz and others (1980) are summarized.

#### ACKNOWLEDGMENTS

U.S. Geological Survey colleagues with previous experience in the Wet Mountains area have freely discussed various aspects of the geology and, in some instances, have contributed unpublished data. Especially helpful to this project were M.H. Staatz, M.R. Brock, W.N. Sharp, and R.L. Parker. R.O. Rye and J.F. Whalen contributed to an understanding of mineralization by supplying light stable-isotope data. C.E. Hedge analyzed various rocks of the alkaline complexes for rubidium and strontium isotopes. The semiquantitative spectrographic analyses were performed by L.A. Bradley, H.G. Neiman, and N.M. Conklin; the gamma-ray spectrometric analyses were performed by C.M. Bunker and C.A. Bush. I.K. Brownfield provided the mineral separates and the X-ray diffraction data. L.M. Osmonson helped with fieldwork.

Local prospectors and ranchers gladly shared information concerning the history, location, and details of various claims. I am especially indebted to Lawrence C. Knobbe, Earnest Sparling, Robert H. Bliss, Joe Tom-sick, Dennis Shaydak, Ed Lepley, Eugene Griffin, and Allan Ellison. Also, Dolf Fieldman of Congdon and

Carey Company freely shared information and diamond drill core from the Gem Park area.

#### GEOLOGIC SETTING

The terrane occupied by the Wet Mountains thorium deposits consists of a variety of Proterozoic metamorphic and intrusive igneous rocks that have been intruded by a series of alkaline intrusive rocks and associated dikes and veins of early Paleozoic age (pl. 1). The alkaline intrusive rocks comprise three complexes: the McClure Mountain Complex, the Gem Park Complex, and the complex at Democrat Creek. Fenite is found adjacent to the complexes and the thorium deposits. The alkaline intrusive rocks are partly covered by a variety of Tertiary volcanogenic rocks and Quaternary sediments.

#### PROTEROZOIC METAMORPHIC ROCKS

Host rocks for the Wet Mountains thorium deposits consist chiefly of Proterozoic metasedimentary and metavolcanic rocks, especially in the area south of the alkaline complexes. The rocks are chiefly migmatitic gneisses that contain quartz, biotite, microcline, and plagioclase interlayered with hornblende gneiss, biotite gneiss, calc-silicate gneiss, and garnet- and sillimanite-bearing gneisses. Brock and Singewald (1968) have further subdivided the various gneisses on the basis of variation in the proportions of the major minerals in the rocks. They included in their Proterozoic gabbroic gneiss and metamorphosed ultramafic rocks unit some Paleozoic ultramafic rocks. As pointed out by Heinrich and Dahlem (1966), some of these rocks are part of the complex at Democrat Creek and are discussed in this report with the alkaline rocks. Some of the ultramafic rocks, such as those in the roadcut of Highway 96 about 11 km east of Silver Cliff, are not typical of alkaline rocks but appear to be cumulates with tholeiitic affinities. One specimen from the roadcut contained oikocrysts of hypersthene 5 cm across, green spinel, apatite, olivine, magnetite, and green amphibole. Although contact relationships with the enclosing rocks are not always clear, some of these ultramafic rocks, such as those in the roadcut, most likely are Proterozoic in age rather than early Paleozoic, and they do not show obvious evidence of metamorphism.

#### EARLY AND MIDDLE PROTEROZOIC GRANITIC ROCKS

Early Proterozoic quartz diorite and granodiorite are fairly common in the northern part of the Royal Gorge and Cotopaxi quadrangles (Taylor and others, 1975a,

b). These rocks have been dated at 1.72 b.y. (billion years), and belong to the Routt Plutonic Suite (Tweto, 1987), which includes the Boulder Creek Granodiorite. Granitic rocks in the Cotopaxi quadrangle have been dated at 1.45 b.y., belong to the Berthoud Plutonic Suite (Tweto, 1987) and thus correlate with Silver Plume Quartz Monzonite (Taylor and others, 1975a). Scott and others (1976) renamed the "r" granite of Brock and Singewald (1968) in the Mount Tyndall quadrangle the San Isabel Granite (Boyer, 1962), which also correlates with the Silver Plume Quartz Monzonite. Rocks mapped as San Isabel Granite become more abundant toward the southeastern part of the area (Taylor, 1974; Scott and others, 1976).

The "r" granite of Brock and Singewald (1968) was reported by them to possess relatively high radioactivity on a scintillation counter—1.5–2.5 times that of other granitic rocks. Five samples of this granitic rock were collected during this study and found to contain 1.78–2.39 ppm (parts per million) RaeU (radium-equivalent uranium), and averaging 2.09 ppm RaeU; they also contain 10.29–28.48 ppm thorium, averaging 18.81 ppm thorium (table 1). Wedepohl's (1971) average igneous rocks of the upper continental crust contain 3.5 ppm uranium and 11 ppm thorium. Thus, the higher radioactivity in the "r" granite appears to be due to thorium. The "r" granite also contains more abundant barium, lanthanum, cerium, and neodymium than the average igneous rocks (table 1). Petrographic and heavy mineral studies of the same five samples indicate that sphene and apatite are the most likely sources of uranium, thorium, and rare-earth elements.

#### CAMBRIAN ALKALINE INTRUSIVE COMPLEXES

Alkaline rocks in the Wet Mountains area occur in three distinct intrusive complexes: the McClure Mountain Complex, the Gem Park Complex, and the complex at Democrat Creek (Armbrustmacher, Brownfield, and Osmonson, 1979; Armbrustmacher and Hedge, 1982; Armbrustmacher, 1984). Additional alkaline intrusive rocks, comprising lamprophyre, carbonatite, and red syenite, are found as dikes that appear to be spatially and genetically related to the intrusive complexes. The quartz-barite-thorite veins also appear to be related to this episode of alkaline magmatism.

The McClure Mountain Complex contains nepheline syenite, hornblende-biotite syenite, mafic nepheline-clinopyroxene rocks, and mafic-ultramafic cumulate rocks (Shawe and Parker, 1967). The Gem Park Complex contains mafic-ultramafic cumulate rocks nearly identical to those in the McClure Mountain Complex, and a single exposure of nepheline syenite pegmatite

(Parker and Sharp, 1970, p. 6). The complex at Democrat Creek is different: it contains quartz syenite, breccia, and mafic-ultramafic rocks. The latter were mapped by Brock and Singewald (1968) as Precambrian gabbroic gneisses and metamorphosed ultramafic rocks but were thought by Heinrich and Dahlem (1966) to be similar to the gabbros and pyroxenites of the Gem Park and McClure Mountain Complexes. The intrusive rocks at Democrat Creek are less notable for their similarities to the rocks of the other two complexes than for their differences.

The intrusive complexes and associated dikes are 520 m.y. (million years) old, according to Olson and others (1977, p. 683). Their dating of leucocratic rocks from the McClure Mountain Complex and the complex at Democrat Creek by fission-track, potassium-argon, and rubidium-strontium techniques could not resolve the differences in the ages of the various complexes or in the ages of different syenites at McClure Mountain. However, subsequent rubidium and strontium isotopic determinations by C.E. Hedge (Armbrustmacher and Hedge, 1982), yielded ages of  $535 \pm 5$  m.y. for syenites at McClure Mountain and  $511 \pm 8$  m.y. for syenites at Democrat Creek.

The petrology of the Wet Mountains alkaline rocks, as outlined by major- and minor-element contents, suggests the presence of several different rock series (Armbrustmacher, 1984). Data on rubidium, strontium, rare-earth elements, and strontium isotopes show that rocks of the complexes did not form through fractionation of a single magma but formed instead as end products of several magmas generated from different source materials (Armbrustmacher and Hedge, 1982).

#### FENITE

Alkali metasomatism has formed fenite in the rocks adjacent to the alkaline intrusive rocks, carbonatite dikes, and quartz-barite-thorite veins in the Wet Mountains area. Fenite forms when sodium and/or potassium and ferric iron oxides are added to host rocks and silica is removed. Host rocks with original granitic compositions typically show progressively greater alteration toward nepheline syenite compositions nearer the alkaline intrusives. Original mafic minerals in the granitic rocks are replaced by sodic pyroxenes and amphiboles; original potassic and sodic feldspars are replaced by another potassic or sodic feldspar that contains abundant ferric iron oxide so that the entire rock takes on a pink color; original quartz is removed. Fenite adjacent to thorite-bearing veins emits a fetid odor when struck with a hammer. This same odor can be obtained from the vein material. Lawrence Knobbe (oral

TABLE 1.—*Chemical analyses of "r" granite from the Wet Mountains area, Colorado*

[Semiquantitative spectrographic analyses by H.G. Neiman; gamma-ray spectrometric analyses by C.A. Bunker and C.A. Bush. Abundance of elements in igneous rocks of upper continental crust given for comparison; data from Wedepohl (1971, p. 65)]

Element	Sample No.					Average	Average of Igneous Rocks in Upper Crust
	192	193	194	195	196		
Semiquantitative spectrographic analyses, in percent							
Fe.....	5.	3.	3.	3.	5.	3.8	3.54
Mg.....	.7	.5	.5	.5	.5	.54	1.39
Ca.....	1.	3.	.7	.7	.7	1.22	2.87
Ti.....	.5	.5	.3	.3	.5	.42	.47
Mn.....	.1	.07	.05	.05	.07	.068	.069
Ba.....	.2	.2	.15	.2	.15	.18	.059
Be.....	.0003	.0002	.0002	.0002	.0003	.00024	.0002
Co.....	.0005	.0005	.0005	.0005	.0005	.0005	.0012
Cr.....	.0005	.0003	.00015	.0002	.0003	.0003	.007
Cu.....	.002	.0015	.0007	.001	.0015	.0013	.003
La.....	.01	.03	.015	.015	.02	.018	.0044
Nb.....	.003	.005	.002	.003	.005	.0036	.002
Pb.....	.003	.003	.005	.003	.003	.0034	.0015
Sc.....	.001	.001	.0007	.0007	.0007	.0008	.0014
Sr.....	.05	.05	.03	.03	.02	.036	.029
V.....	.007	.005	.003	.003	.01	.0056	.0095
Y.....	.01	.01	.005	.007	.01	.0084	.0034
Zr.....	.03	.03	.05	.07	.05	.046	.016
Si.....	>10.	>10.	>10.	>10.	>10.	>10.	>10.
Al.....	7.	10.	10.	7.	7.	8.2	7.83
Na.....	3.	3.	3.	3.	3.	3.	2.45
Ce.....	.03	.03	.03	.03	.05	.034	.0075
Ga.....	.003	.003	.002	.003	.002	.0026	.0017
Yb.....	.001	.001	.0005	.0007	.001	.0008	.00034
Nd.....	.015	.02	.015	.015	.02	.017	.003
Gamma-ray spectrometric analyses, in parts per million							
Rae U..	2.21	2.26	1.79	1.78	2.39	2.09	3.5
Th.....	14.62	10.29	21.18	19.49	28.48	18.81	11.
K.....	4.64	4.83	4.89	4.71	4.62	4.74	2.82

commun., 1976) said that when a dynamite blast opened a section of thorite-bearing vein, the odor from the associated fenite was strong enough to give the prospectors headaches if they entered the newly created hole too soon. This characteristic odor has been discussed by Heinrich and Anderson (1965), Christman and others (1953), Singewald and Brock (1956), and Christman and

others (1959). It has also been noted in other thorium districts.

The odor-producing gas contains a variety of hydrocarbon compounds as well as sulfur-bearing compounds (Heinrich and Anderson, 1965, and G.E. Claypool, oral commun., 1978). The odoriferous material may be the fugitive constituents of complexing agents

that combined with thorium to produce a highly mobile species capable of being transported under pressure-temperature conditions that existed in the hydrothermal solutions. The complexing of thorium in low-temperature environments is discussed by Langmuir and Herman (1980).

Response of mafic rocks, alkaline and tholeiitic, to fenitizing solutions is considerably different than granitic rocks. The end product of fenitization of mafic rocks is usually a rock containing abundant vermiculite. Mafic-ultramafic rocks near the center of the Gem Park Complex have been vermiculitized and that material was exploited at one time at the Vermiculite mine. Parker and Sharp (1970) suggested that the vermiculitized area occurs over a central core of carbonatite. However, holes drilled in this area passed through vermiculitized rock into relatively fresh mafic-ultramafic rocks. Vermiculite zones also occur at the Niles mine, in Gem Park, where carbonatite dikes intersect mafic-ultramafic rocks of the Gem Park Complex. The mafic-ultramafic rocks at the contact are strongly vermiculitized for a width of about 1 m.

#### TERTIARY VOLCANOGENIC ROCKS AND QUATERNARY SEDIMENTS

Tertiary and Quaternary rocks postdate the thorium deposits in the Wet Mountains area. Scott and Taylor (1975) and Sharp (1978) described these rocks in detail. Because these rocks are considerably younger than the thorium deposits and have no relationship to thorium deposit genesis, they will not be discussed.

#### THORIUM DEPOSITS

Thorium in the Wet Mountains area is found in three kinds of deposits: carbonatites, red syenite dikes, and quartz-barite-thorite veins and fracture zones (Armbrustmacher, 1976). Some exploration has been done in carbonatites, especially those in and around the Gem Park Complex, principally in search of economic deposits of niobium and rare-earth elements. Most of the exploration for thorium, however, has been directed toward locating the quartz-barite-thorite veins and fracture zones, where higher concentrations of thorium have been found.

#### CARBONATITES

Carbonatite dikes and irregularly shaped intrusions in and near the McClure Mountain and Gem Park Complexes form two distinct groups, replacement and

primary magmatic, as determined chiefly by differences in petrography (Armbrustmacher, 1979; Armbrustmacher and Brownfield, 1978). Replacement carbonatites show textures indicating pseudomorphous replacement of an originally porphyritic or hypidiomorphic-granular rock by carbonate mineral. They contain an element suite characteristic of carbonatites as well as a trace-element signature indicative of a mafic-silicate precursor. Primary magmatic carbonatites, which are typically equigranular and lack obvious replacement textures, are also enriched in elements characteristic of carbonatites but contain average amounts of these elements greater than replacement carbonatites. The carbonatites found in and around the Gem Park Complex appear to form a subgroup within the primary magmatic group because of differences in mineralogy and geochemistry.

#### REPLACEMENT CARBONATITES

Replacement carbonatites occur chiefly as dikes. The rocks are dark green, dark greenish brown, dark reddish brown, purple, or maroon on weathered surfaces; fresh rock surfaces of individual dikes have similar colors, but the color of the weathered and fresh surfaces is not necessarily the same. Radioactivity of the dikes does not exceed about 5-8 times background with stronger radioactivity typically occurring along contacts, especially if they are sheared. The host rock is invariably fenitized to varying degrees, seldom extending more than several centimeters from the contact, and the fenite may also be anomalously radioactive.

Carbonate minerals in replacement carbonatites are fine to medium grained and replace preexisting minerals as aggregated pseudomorphs so that the original texture is retained. The porphyritic rocks most likely to have been replaced appear to be lamprophyres similar to those found throughout the area. Partial replacement of phenocrysts in the lamprophyres by carbonate and other minerals is often observed, suggesting the possibility that a continuous series may exist between fresh, unaltered lamprophyre and replacement carbonatite. Partial replacement of potassic feldspar by carbonate minerals in various red syenite dikes and the presence of feldspar remnants in some of the replacement carbonatites suggests that the syenite dikes were parent rocks of some of the carbonatites.

The replacement carbonatites occur chiefly southeast of the McClure Mountain Complex as shown on plate 1. The only replacement carbonatites found thus far north of the complex occur along the Ilse fault and near the contact of the complex with the country rock. Lamprophyres and red syenites, which may be the original

material of some of the replacement carbonatites, are abundant throughout the area (Heinrich and Dahlem, 1966, 1969).

#### MINERALOGY

The replacement carbonatites contain a fairly large variety of minerals, although not as many as the primary magmatic carbonatites (table 2), based on Armbrustmacher (1979) and Armbrustmacher and Brownfield (1978). Calcite/dolomite ratios are variable although calcite is usually more abundant. Magnesite was also identified in a few samples. Barite is a common constituent but has a highly variable distribution along strike. Ferric oxide minerals are fairly abundant and occur as primary specular hematite, as goethite replacing pyrite in pseudomorphs, and as secondary hematitic and amorphous intergranular stain. Quartz, microcline, albite, acmite, and biotite occur in at least minor amounts, but microcline can be present in major amounts. Accessory minerals that are probably responsible for the rare-earth and thorium content include fluorapatite, sphene, and zircon, and sparse bastnaesite, monazite, and xenotime. Magnetite, spinel, and rutile are also common accessory minerals. Alpha-counter measurements of handpicked concentrates of iron oxide minerals sometimes show anomalous radioactivity that may be due to minor amounts of metamict thorite or monazite associated with the iron oxides.

#### GEOCHEMISTRY

The replacement carbonatites in the Wet Mountains contain at least twice the average amount of calcium, barium, lanthanum, niobium, strontium, yttrium, and cerium as the average igneous rocks of the upper continental crust, as reported by Wedepohl (1971) (table 3). High values for these elements are characteristic of carbonatites (Heinrich, 1966, p. 222; Gold, 1963). The carbonatites also contain more abundant manganese, cobalt, chromium, scandium, and nickel than crustal averages (table 3). This group of elements is typically more abundant in mafic and ultramafic igneous rocks (Goles, 1967) and also apparently is abundant in lamprophyres (Armbrustmacher, 1979) relative to crustal igneous rocks. The major elements silicon, aluminum, sodium, potassium, iron, magnesium, and titanium are more abundant in replacement carbonatites than in primary carbonatites and, with the exception of magnesium, in carbonatites found at Gem Park (table 3). This reflects the abundance of rock-forming silicates, especially potassic feldspars, sodic amphiboles, and sodic pyroxenes, in replacement carbonatites relative

to primary magmatic carbonatites and Gem Park carbonatites. The major- and trace-element abundances in replacement carbonatites seem compatible with the suggestion that the rocks were originally either lamprophyres or red syenites.

#### PRIMARY MAGMATIC CARBONATITES

Primary magmatic carbonatites occur chiefly in dikes ranging in thickness from a few centimeters to about 3 m—a typical thickness is 1 m. However, southeast of Gem Park, primary magmatic carbonatite occurs in a plug-shaped mass about 30 m in diameter (Parker and Sharp, 1970, p. 9). Primary magmatic carbonatite weathers to a dark reddish brown to dark brown color. On fresh surfaces this rock is commonly white, although in some places, it is similar in color to replacement carbonatites; it is brown, greenish brown, or (rarely) bluish gray on fresh surfaces. Primary magmatic carbonatites typically contain 10 times as much radioactivity as adjacent host rocks and have been of economic interest because of local concentrations of thorium as well as rare-earth elements and niobium.

At the outcrop these rocks tend to be quite coarse grained—carbonate grains 4 cm across are common. Carbonatite near the contact with host rocks tends to form a fine-grained chill zone, but the maximum grain size is usually attained within a few centimeters of the contact.

Lamprophyre dikes are sometimes found in close proximity with primary magmatic carbonatite dikes. According to Heinrich and Dahlem (1966), the carbonatite is typically younger than the associated lamprophyre. However, the sequence of intrusion of various members of the alkaline sequence may be more complicated than they indicate: at one locality near the southeast side of the McClure Mountain Complex, a primary magmatic carbonatite is intruded by a lamprophyre dike (Armbrustmacher and others, 1979). Hence, rather than sharing a direct genetic relationship, the carbonatites and lamprophyres may only occupy the same zones of structural weakness within the host rock.

All the primary magmatic carbonatites thus far examined occur within one of the three alkaline intrusive complexes, or at a distance less than 6.5 km from the complexes. The carbonatites are especially numerous west of the McClure Mountain Complex, east of the McClure Mountain Complex along Bear Creek, and in and adjacent to the Gem Park Complex.

#### MINERALOGY

There is a greater variety of minerals, especially rare-earth minerals, in the primary magmatic carbonatites

TABLE 2.—*Mineralogy of carbonatites from the Wet Mountains area, Colorado*

[C, common, present in greater than 50 percent of the samples. M, moderately common, present in 20-50 percent of the samples. R, rare, present in 5-20 percent of the samples. VR, very rare, present in less than 5 percent of the samples. Leaders (---), not identified. Taken from Armbrustmacher, 1979, p. 892]

Mineral	Formula	Abundance in Carbonatites		Mineral	Formula	Abundance in Carbonatites	
		Primary	Replacement			Primary	Replacement
Actinolite.....	$\text{NaFe}^{+3}\text{Si}_2\text{O}_6$	R	M	Magnetite.....	$\text{MgCO}_3$	---	R
Actinolite.....	$\text{Ca}_2(\text{Mg}, \text{Fe}^{+2})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	---	VR	Magnetite.....	$\text{Fe}^{+2}\text{Fe}_2\text{O}_4$	R	M
Anatase.....	$\text{TiO}_2$	R	---	Microcline.....	$\text{KAlSi}_3\text{O}_8$	M	C
Ancylite.....	$\text{SrCe}(\text{CO}_3)_2(\text{OH})\cdot\text{H}_2\text{O}$	R	---	Monazite.....	$(\text{Ce}, \text{La}, \text{Nd}, \text{Th})\text{PO}_4$	R	R
Ankerite.....	$\text{Ca}(\text{Fe}^{+2}, \text{Mg}, \text{Mn})(\text{CO}_3)_2$	R	---	Muscovite.....	$\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH}, \text{F})_2$	VR	---
Barite.....	$\text{BaSO}_4$	C	M	Phlogopite.....	$\text{KMg}_3\text{Si}_3\text{AlO}_{10}(\text{F}, \text{OH})_2$	R	M
Bastnaesite.....	$(\text{Ce}, \text{La})(\text{CO}_3)\text{F}$	M	VR	Plagioclase....	$(\text{Na}, \text{Ca})\text{Al}(\text{Al}, \text{Si})\text{Si}_2\text{O}_8$	VR	R
Biotite.....	$\text{K}(\text{Mg}, \text{Fe}^{+2})_3(\text{Al}, \text{Fe}^{+3})\text{Si}_3\text{O}_{10}(\text{OH}, \text{F})_2$	R	M	Pyrite.....	$\text{FeS}_2$	M	R
Calcite.....	$\text{CaCO}_3$	C	C	Pyrochlore.....	$(\text{Na}, \text{Ca})_2\text{Nb}_2\text{O}_6(\text{OH}, \text{F})$	R	---
Cancrinite.....	$\text{Na}_6\text{Ca}_2\text{Al}_6\text{Si}_6\text{O}_{24}(\text{CO}_3)_2$	VR	---	Quartz.....	$\text{SiO}_2$	C	C
Cerussite.....	$\text{PbCO}_3$	VR	---	Rutile.....	$\text{TiO}_2$	M	M
Chalcophyllite...	$\text{CuFeS}_2$	---	R	Siderite.....	$\text{FeCO}_3$	VR	---
Chlorite.....	$(\text{Mg}, \text{Al}, \text{Fe})_{12}(\text{Si}, \text{Al})_8\text{O}_{20}(\text{OH})_{16}$	R	---	Sphalerite.....	$(\text{Zn}, \text{Fe})\text{S}$	VR	---
Chromite.....	$\text{Fe}^{+2}\text{Cr}_2\text{O}_4$	---	VR	Sphene.....	$\text{CaTiSiO}_5$	R	VR
Crocidolite.....	$\text{Na}_2(\text{Fe}^{+2}, \text{Mg})_3\text{Fe}_2^{+3}\text{Si}_8\text{O}_{22}(\text{OH})_2$	VR	VR	Spinel.....	$\text{MgAl}_2\text{O}_4$	VR	R
Diopside.....	$\text{CaMgSi}_2\text{O}_6$	---	VR	Strontianite...	$\text{SrCO}_3$	R	---
Dolomite.....	$\text{CaMg}(\text{CO}_3)_2$	C	M	Synchysite....	$(\text{Ce}, \text{La})\text{Ca}(\text{CO}_3)_2\text{F}$	M	---
Epidote.....	$\text{Ca}_2(\text{Al}, \text{Fe}^{+3})_3(\text{SiO}_4)_3(\text{OH})$	R	VR	Thorite.....	$\text{ThSiO}_4$	VR	---
Fluorapatite....	$\text{Ca}_5(\text{PO}_4)_3\text{F}$	M	R	Vermiculite....	$(\text{Mg}, \text{Fe}^{+2}, \text{Al})_3(\text{Al}, \text{Si})_4\text{O}_{10}(\text{OH})_2\cdot 4\text{H}_2\text{O}$	R	R
Fluorite.....	$\text{CaF}_2$	R	---	Xenotime.....	$\text{YPO}_4$	VR	R
Galena.....	$\text{PbS}$	VR	---	Zircon.....	$\text{ZrSiO}_4$	VR	VR
Goethite.....	$\alpha\text{-Fe}^{+3}\text{O}(\text{OH})$	M	M				
Hematite.....	$\alpha\text{-Fe}_2\text{O}_3$	C	C				
Ilmenite.....	$\text{Fe}^{+2}\text{TiO}_3$	VR	---				
Lepidocrocite..	$\gamma\text{-Fe}^{+3}\text{O}(\text{OH})$	R	---				

TABLE 3.—*Arithmetic means and ranges of elements in carbonatites from the Wet Mountains area, Colorado, and other comparative rocks*

[Data in percent. Leaders (---), no analyses. Mean values of elements in other rock series have been included for comparative purposes]

Element	1. Replacement carbonatite		2. Primary magmatic carbonatite		3. Carbonatites from Gem Park		4. Average carbonate (Mean)		5. Average igneous rocks		6. Average sedimentary carbonate rocks		7. Lamprophyre (Mean)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Fe.....	6.0	2-10.	5.4	0.5-10.	3.6	1.5-10.	5.1	1.5-10.	3.54	3.54	0.42	0.42	>10.	>10.
Mg.....	3.3	1-7.	1.9	.02-7.	6.6	.15-10.	3.4	.15-10.	1.39	1.39	4.8	4.8	1.5	1.5
Ca.....	>10.	1.5-10.	>10.	.5-10.	>10.	7.0-10.	>10.	7.0-10.	2.87	2.87	>10.	>10.	.6	.6
Ti.....	.61	.003-2.	.24	<0.0002-1.	.07	<0.0002-1.5	.5	<0.0002-1.5	.47	.47	.03	.03	1.2	1.2
Mn.....	.23	.05-2.	.66	.02-3.	.6	.1-1.	.5	.1-1.	.069	.069	.05	.05	.2	.2
Ba.....	.53	.015-10.	1.5	.0015-10.	.7	.007-10.	.23	.007-10.	.059	.059	.015	.015	.3	.3
Be.....	.0007	<0.0001-0.002	.0008	<0.0001-0.01	---	---	---	---	.0002	.0002	.0001	.0001	.004	.004
Co.....	.0033	<0.0003-0.03	.0016	<0.0005-0.03	.0014	.0003-0.003	.0017	.0003-0.003	.0012	.0012	.0004	.0004	.007	.007
Cr.....	.047	.0015-0.2	.011	<0.0001-0.07	.005	<0.0001-0.07	.0048	<0.0001-0.07	.007	.007	.0009	.0009	.07	.07
Cu.....	.0039	.0002-0.02	.0043	<0.0001-0.02	.0029	<0.0001-0.07	.0002	<0.0001-0.07	.003	.003	.0014	.0014	.006	.006
La.....	.023	<0.005-0.5	.65	<0.002-3.	.54	<0.005-3.	.052	<0.005-3.	.0044	.0044	.0014	.0014	.01	.01
Mo.....	.0004	<0.0003-0.003	.0009	<0.0003-0.007	<0.0003	<0.0003-0.0015	.0042	<0.0003-0.0015	.0001	.0001	.0001	.0001	.002	.002
Nb.....	.014	<0.001-0.2	.0068	<0.001-0.03	.07	<0.001-0.7	.2	<0.001-0.7	.002	.002	---	---	.03	.03
Ni.....	.020	<0.0005-0.1	.0051	<0.0005-0.03	.0013	<0.0005-0.03	.0008	<0.0005-0.03	.0044	.0044	.0012	.0012	.07	.07
Pb.....	.0084	<0.001-0.1	.018	<0.001-0.5	.0083	<0.001-0.02	---	<0.001-0.02	.0015	.0015	.0008	.0008	.0045	.0045
Sc.....	.0025	.0007-0.015	.0025	<0.0005-0.05	.0018	<0.0005-0.007	.001	<0.0005-0.007	.0014	.0014	.00003	.00003	.005	.005
Sr.....	.088	.015-0.2	.32	.007-5.	1.8	.07-7.	.34	.07-7.	.029	.029	.047	.047	.02	.02
V.....	.024	.003-0.05	.012	<0.0007-0.1	.0034	<0.0007-0.03	---	<0.0007-0.03	.0095	.0095	.0015	.0015	.03	.03
Y.....	.015	.0015-0.15	.049	.002-0.7	.013	.001-0.05	.01	.001-0.05	.0034	.0034	.0013	.0013	.01	.01
Zr.....	.015	<0.001-0.07	.013	<0.001-0.2	.0031	<0.001-0.03	.11	<0.001-0.03	.016	.016	.0017	.0017	.01	.01
Si.....	>10.	2.0-10.	6.8	1-10.	1.1	.01-7.	5.7	.01-7.	30.54	30.54	2.4	2.4	>10.	>10.
Al.....	4.3	.3-10.	2.3	.02-10.	.2	.03-2.	1.9	.03-2.	7.83	7.83	.43	.43	5.	5.
Na.....	3.3	<0.05-10.	1.3	<0.05-10.	.4	<0.05-0.7	.3	<0.05-0.7	2.45	2.45	.04	.04	1.1	1.1
K.....	4.8	<0.7-10.	2.6	<0.7-10.	<0.7	<0.7-2.	1.2	<0.7-2.	2.82	2.82	.27	.27	7.	7.
P.....	<0.2	<0.2-1.5	.6	<0.2-10.	1.4	<0.2-10.	.85	<0.2-10.	.081	.081	.02	.02	.1	.1
Ce.....	.038	<0.01-1.	.61	<0.01-2.	.64	.01-3.	.15	.01-3.	.0075	.0075	---	---	.02	.02
Ga.....	.0013	<0.0005-0.003	.0007	<0.0005-0.003	<0.0005	<0.0005-0.002	.0001	<0.0005-0.002	.0017	.0017	.0002	.0002	.001	.001
Yb.....	.0011	<0.0001-0.007	.0075	<0.0001-0.3	.0006	<0.0001-0.005	---	<0.0001-0.005	.00034	.00034	---	---	.001	.001
Pr.....	<0.01	<0.01-0.01	.16	<0.01-0.7	.23	<0.01-1.5	---	<0.01-1.5	.00076	.00076	---	---	<0.01	<0.01
Nd.....	.025	<0.007-0.7	.30	<0.007-2.	.28	<0.007-3.	---	<0.007-3.	.003	.003	---	---	.01	.01
Sm.....	<0.01	<0.01-0.01	.055	<0.01-0.3	.036	<0.01-0.3	---	<0.01-0.3	.00066	.00066	---	---	<0.01	<0.01
Eu.....	<0.007	<0.007-0.01	.0083	<0.007-0.03	.007	<0.007-0.015	---	<0.007-0.015	.00014	.00014	---	---	<0.007	<0.007
2TlREE..	.084	---	1.55	---	1.6	---	---	---	.016	.016	---	---	.04	.04
3TlREE..	.018	---	.087	---	.019	---	---	---	.0059	.0059	---	---	.015	.015
Th.....	.013	.0004-0.06	.15	.0013-1.8	---	---	---	---	.0011	.0011	.0002	.0002	.012	.012
RaU... ..	.0005	.00002-0.0036	.0026	.00002-0.012	---	---	---	---	.00035	.00035	.0002	.0002	.0004	.0004

<sup>1</sup>Total light rare-earth elements, La+Ce+Pr+Nd+Sm+Eu.<sup>2</sup>Total heavy rare-earth elements, Y+Ce+Tb+Dy+Ho+Er+Tm+Lu+Yb.<sup>3</sup>Radium-equivalent uranium.

## SAMPLES AND METHODS OF ANALYSIS

1. Replacement carbonatite, Wet Mountains area. Based on 6-step semiquantitative spectrographic and gamma ray spectrometric (RaeU and Th) analyses (Armbrustmayer and Brownfield, 1978). Number of samples = 8.
2. Primary magmatic carbonatite, Wet Mountains area. Based on 6-step semiquantitative spectrographic analyses (Armbrustmayer and Brownfield, 1978). Number of samples = 52.
3. Carbonatites from Gem Park, Wet Mountains area. Means and ranges calculated from data in Parker and Sharp (1970, table 11). Number of samples = 39.
4. Average carbonatite; partly recalculated from Gold (1963, p. 989, col. III).
5. Abundance of elements in the igneous rocks of the upper continental crust (Wedepohl, 1971, table 7.3, p. 65).
6. Average concentrations in sedimentary carbonate rocks; minor elements from Graf (1960a, p. 71), major elements from Graf (1960b, p. 24, col. 6).
7. Average of lamprophyre samples 407 and 410 from Wet Mountains area. Both are altered and may be somewhat mineralized.

than in the replacement carbonatites (table 2). White calcite is typically the major constituent. Bastnaesite is a fairly common constituent, having been identified in nearly 50 percent of the samples. Usually the bastnaesite is associated with synchysite and, rarely, with ancylite and strontianite. Other rare-earth-bearing minerals include monazite, xenotime, and fluorapatite. Dolomite is common, and strontianite and ankerite are rare. Quartz, hematite, and barite are common and present in variable amounts; microcline is also quite common. Of the sulfides, pyrite is more common than sphalerite or galena; pyrite is also more common than the alteration product of galena—cerussite. Thorite, fluorite, and pyrochlore were also identified in a limited number of samples. Most of the minerals found in replacement carbonatites are also found in the primary magmatic carbonatites.

#### GEOCHEMISTRY

The primary magmatic carbonatite contains at least twice, and as much as 21 times, as much sodium, potassium, barium, chromium, copper, lanthanum, nickel, scandium, yttrium, cerium, and gallium as the "average carbonatite" of Gold (1963), based on the mean values in 52 samples (table 3). On the other hand, titanium, molybdenum, niobium, and zirconium are depleted. Compared with average crustal igneous rocks, as reported by Wedepohl (1971), primary magmatic carbonatites contain 6–132 times as much manganese, barium, strontium, niobium, lanthanum, cerium, yttrium, and thorium. Relative to replacement carbonatites, primary magmatic carbonatites contain at least twice as much manganese, barium, lanthanum, lead, strontium, yttrium, ytterbium, cerium,  $\Sigma$ LREE (total light rare-earth elements), and  $\Sigma$ HREE (total heavy rare-earth elements). The rock-forming minerals—reflected by the abundances of silicon, aluminum, sodium, potassium, iron, and titanium—appear to be greater in the subgroup of primary magmatic carbonatites of Gem Park than in primary magmatic carbonatites (table 3).

#### SELECTED CARBONATITE OCCURRENCES

Several individual carbonatite intrusions or groups of intrusions have been selected for further discussion because of their unusual mineralogy or relative economic importance. Most are primary magmatic carbonatites.

##### GOLDIE CARBONATITE

The aluminofluoride mineral assemblage in the Goldie carbonatite (near lat 38°22' N., long 105°32' W.) reported by Heinrich and Anderson (1965), Heinrich and

Quon (1963), and Heinrich (1965, 1977) has not been observed in other carbonatites in the Wet Mountains area. The carbonatite consists of coarse-grained calcite with intergranular patches of finer grained carbonate, albite, barite, and unusually large amounts of fluorite. Late replacement nodules contain cryolite, pachnolite, ralstonite, weberite, prosopite, fluorite, and sericite (Heinrich, 1977). Semiquantitative spectrographic analysis of several carbonatite samples shows that they contain more iron, magnesium, manganese, and barium than the average primary magmatic carbonatite (table 3; Armbrustmacher and Brownfield, 1978). They also contain more of the other typical carbonatite elements, such as rare-earth elements, strontium, niobium, and thorium, than are found in igneous rocks of the upper continental crust (Wedepohl, 1971; table 3), but less than are found in primary magmatic carbonatites (table 3).

##### AMETHYST CARBONATITE

Amethyst forms veins within a rock (near lat 38°31'30" N., long 105°25'30" W.) described as silico-carbonatite by Heinrich and Shappirio (1966). This is the only known occurrence of amethyst in a carbonatite within the Wet Mountains area. The silico-carbonatite dikes and associated fenite occur along the Ilse fault more than 16 km north of the McClure Mountain Complex (pl. 1); these dikes are found farther from the alkaline intrusive complexes than any other carbonatite. Examination of thin sections of the silico-carbonatite shows it to be intensely brecciated with small remanent grains and grain clusters of quartz, microcline, and barite. The interstitial material appears to be very fine grained, poorly sorted fragments of the same minerals. Calcite veins cut across the rock and partly replace some parts of it. Heavy mineral separates of the same rocks yielded hematite, goethite, and barite but no rare-earth or thorium-bearing minerals. Semiquantitative spectrographic analysis of the same rocks shows variable barium (0.01–7.0 percent), variable strontium (0.0005–0.2 percent), and low total rare-earth content (0–0.18 percent). Other elements characteristic of carbonatites are present in low concentrations (Armbrustmacher and Brownfield, 1978). Gamma-ray spectrometric analysis yields 145–1,180 ppm thorium and 0.5–408 ppm uranium. The mineral content, rock texture, and element content show almost no similarities to primary magmatic carbonatites that occur farther south. Because of the replacement textures, these rocks appear to be replacement carbonatites.

##### MCCLURE GULCH CARBONATITE

The multiple carbonatite (near lat 38°20' N., long 105°27' W.) that intrudes the McClure Mountain



Complex at McClure Gulch (pl. 1) appears to have several unique aspects (Armbrustmacher, Brownfield, and Osmonson, 1979). This primary magmatic carbonatite dike shows two separate and distinct kinds of carbonatite that persist side-by-side in a discontinuous manner with a consistent thickness along the entire length of the dike. A sulfide-bearing phase contains unusually large amounts of pyrite and sparse disseminated sphalerite (table 4). Strontianite and ancylite,

which have not been identified at other carbonatite localities other than Gem Park, are closely associated with bastnaesite and synchysite. A coarse-grained phase, adjacent to but older than the sulfide-bearing phase, does not contain sulfide- or strontium-bearing minerals but does contain pyrochlore, which has also been found only at Gem Park. This is also the only known locality where a lamprophyre dike intrudes carbonatite.

TABLE 4.—*Mineralogy of carbonatites from McClure Gulch, Wet Mountains area, Colorado*

[C, common constituent; M, moderately common; R, rare; query (?), data insufficient for positive identification; leaders (---), not identified. Identifications are based on data obtained by X-ray diffraction and microscopic examination. Taken from Armbrustmacher, Brownfield, and Osmonson, 1979, p. 41]

Mineral	Formula	Abundance of Carbonatites	
		Coarse-grained	Sulfide-bearing
Ancylite.....	$\text{SrCe}(\text{CO}_3)_2(\text{OH}) \cdot \text{H}_2\text{O}$ .....	?	M
Ankerite.....	$\text{Ca}(\text{Fe}^{+2}, \text{Mg}, \text{Mn})(\text{CO}_3)_2$ .....	---	R
Barite.....	$\text{BaSO}_4$ .....	M	M
Bastnaesite.....	$(\text{Ce}, \text{La})(\text{CO}_3)\text{F}$ .....	?	M
Biotite.....	$\text{K}(\text{Mg}, \text{Fe}^{+2})_3(\text{Al}, \text{Fe}^{+3})\text{Si}_3\text{O}_{10}(\text{OH}, \text{F})_2$ ...	R	---
Calcite.....	$\text{CaCO}_3$ .....	C	C
Dolomite.....	$\text{CaMg}(\text{CO}_3)_2$ .....	?	C
Fluorapatite....	$\text{Ca}_5(\text{PO}_4)_3\text{F}$ .....	M	M
Goethite.....	$\alpha\text{-Fe}^{+3}\text{O}(\text{OH})$ .....	M	M
Hematite.....	$\alpha\text{-Fe}_2\text{O}_3$ .....	M	M
Lepidocrocite...	$\gamma\text{-Fe}^{+3}\text{O}(\text{OH})$ .....	?	R
Magnetite.....	$\text{Fe}^{+2}\text{Fe}_2^{+3}\text{O}_4$ .....	?	R
Pyrite.....	$\text{FeS}_2$ .....	---	M
Pyrochlore.....	$(\text{Na}, \text{Ca})_2\text{Nb}_2\text{O}_6(\text{OH}, \text{F})$ .....	R	---
Quartz.....	$\text{SiO}_2$ .....	---	R
Rutile.....	$\text{TiO}_2$ .....	R	---
Sphalerite.....	$(\text{Zn}, \text{Fe})\text{S}$ .....	---	R
Strontianite....	$\text{SrCO}_3$ .....	R	M
Synchysite.....	$(\text{Ce}, \text{La})\text{Ca}(\text{CO}_3)_2\text{F}$ .....	---	M

Analyses of the sulfide-bearing and coarse-grained phases show that the sulfide-bearing carbonatite contains at least twice the average amount of iron, magnesium, manganese, barium, chromium, lanthanum, lead, strontium, vanadium, yttrium, cerium,  $\Sigma$ REE, thorium, and uranium than the coarse-grained carbonatite (table 5). Primary magmatic carbonatites as a group (table 3) contain more abundant magnesium, titanium, manganese, barium, chromium, lanthanum, niobium, nickel, vanadium, zirconium, silicon, aluminum, sodium, potassium, phosphorus, thorium, and uranium than both the sulfide-bearing and coarse-grained carbonatites, due chiefly to the common occurrence of silicate minerals in primary magmatic carbonatites. Both sulfide-bearing and coarse-grained carbonatites contain more abundant strontium than average primary magmatic carbonatites, and this is reflected by the presence of ancylite and strontianite.

#### GEM PARK CARBONATITES

The primary magmatic carbonatites at Gem Park, which occur at various localities, surface and subsurface, within that complex, have been studied by Parker and Sharp (1970) and by Papson (1981). They contain minerals that have not been found in primary magmatic carbonatites elsewhere in the Wet Mountains area. These include columbite, natrolite, pyrrhotite, and thorianite (Parker and Sharp, 1970, p. 12). Minerals found in primary magmatic carbonatites away from Gem Park but not reported from Gem Park include chlorite, epidote, fluorapatite, goethite, hematite, lepidocrocite, microcline, rutile, siderite, synchysite, and thorite. The most important workings in and around Gem Park include the Gem mine, the Niles mine, the Vermiculite mine, and the carbonatite plug at Pine Gulch, 1.3 km east of the south end of the Gem Park Complex (pl. 1).

The carbonatite dike at the Gem mine intrudes rocks of the Gem Park Complex and also Proterozoic granitic gneiss north of the complex. The silicate-bearing carbonatite contains quartz, barite, iron oxide rich carbonate as well as patches of clearer carbonate, ancylite, phlogopite, pyrite, and monazite(?). Eckel (1961) reported the occurrence of niccolite, annabergite, and native silver in ore mined in the late 1900's, presumably from this carbonatite, but none of these minerals was identified in this study. The thorium and rare earth abundances are relatively low (Armbrustmacher and Brownfield, 1978, table 1).

The carbonatite dike at the Niles mine has fenitized the ultramafic rocks that it intrudes to vermiculite-rich rock for a distance of about 1 m away from the contact.

The carbonatite consists of calcite, dolomite, goethite, hematite, magnetite, ilmenite(?), phlogopite, bastnaesite, minor quartz, rutile, and monazite. The bastnaesite and monazite do not appear to coexist in the same hand specimen but their paragenesis is not known. These moderately coarse-grained rocks contain fairly abundant total rare earths (2.8 percent), about 350 ppm thorium, and low concentrations of niobium (less than 30 ppm).

The Vermiculite mine occupies an area of strongly altered ultramafic rocks and only a few small carbonatites occur in the workings. According to Parker and Sharp (1970, p. 22) the vermiculitized rocks may represent the surface expression of an alteration halo around a buried carbonatite stock. However, according to Dolf Fieldman (oral commun., 1978), drill core from the immediate vicinity shows that alteration of the ultramafic rocks ceases at depth without encountering a carbonatite stock.

The carbonatite plug at Pine Gulch is about 30 m in diameter and has abundant blue crocidolite. The rock consists predominantly of calcite and dolomite with interstitial and crosscutting fibrous crocidolite. Also present are magnetite, hematite, goethite, microcline, monazite, and perhaps quartz. The carbonatite contains about 26 ppm thorium, 200 ppm niobium, and 1.2 percent  $\Sigma$ REE.

Parker and Sharp (1970, table 11) reported the analyses of 30 samples of carbonatite at Gem Park. Some differences in the average abundance of elements are noted between these samples and the primary magmatic carbonatites (Armbrustmacher, 1979). The Gem Park carbonatites contain an average of 10 times more niobium, 6 times more strontium, and considerably less silicon, aluminum, sodium, potassium, iron, and titanium (table 3). This is due to lower abundances of rock-forming minerals. The  $\Sigma$ HREE are also somewhat depleted in Gem Park carbonatites.

In a study supported by the U.S. Geological Survey, Papson (1981) investigated the carbonatite at Gem Park from several diamond drill cores of Congdon and Carey Company of Denver, Colo. The list of minerals that he found in the cores is given in table 6. Modal analyses of the carbonatites are given in table 7, and partial chemical analyses are given in table 8.

The results of Papson's (1981) studies show that the Gem Park Complex has at least three types of carbonatite. The oldest type consists of dolomite, fluorapatite, magnetite, and phlogopite with accessory pyrochlore and zircon. It is characterized by low-grade niobium (mean=584 ppm) and rare-earth elements (mean=3,713 ppm). Niobium and the  $\Sigma$ REE occur chiefly in pyrochlore. The presence of uranium (high value=131 ppm) in core samples of carbonatite is

TABLE 5.—Chemical analyses of carbonatites from McClure Gulch, Wet Mountains area, Colorado

[From Armbrustmacher, Brownfield, and Osmonson (1979, p. 44). N.D., no data. Average primary carbonatites based on 52 analyses from Armbrustmacher and Brownfield (1978). Semiquantitative spectrographic analyses by L.A. Bradley; looked for but not found: Ag, As, Au, Be, Bi, Cd, Pd, Pt, Sb, Sn, Te, W, Zn, Ga, Ge, Hf, In, Li, Re, Ta, Tl, Pr, Tm, Lu. Gamma-ray spectrometric analyses by C.M. Bunker and C.A. Bush]

Sample No.	Coarse-grained carbonatite		Sulfide-bearing carbonatite				Average primary carbonatite
	453	455B	419	454	455A	456	
Semiquantitative spectrographic analyses (in percent)							
Fe.....	1.5	1.5	3.	7.	3.	7.	5.2
Mg.....	.2	.2	.5	.15	.15	1.	2.0
Ca.....	>10.	>10.	>10.	>10.	>10.	>10.	>10.
Ti.....	.002	.001	<0.0002	.01	.003	<0.0002	.22
Mn.....	.7	.7	.2	.5	.3	.5	.6
Ba.....	.07	.1	.15	.5	.5	.2	1.5
Co.....	<0.0005	<0.0005	.003	.001	.001	.003	.0016
Cr.....	.0002	.0002	.0003	.0007	.0005	.0007	.014
Cu.....	.003	.0007	.007	.0015	.0015	.0015	.0047
La.....	.05	.07	.15	.2	.2	.3	.56
Mo.....	<0.0003	.0005	.0007	<0.0003	.0005	.0007	.007
Nb.....	.001	.005	<0.001	.005	<0.001	.0015	.007
Ni.....	<0.0005	.0015	.001	<0.0005	<0.0005	.0007	.0055
Pb.....	.002	.003	.01	.01	.015	.015	.002
Sc.....	<0.0005	.001	.0015	.0015	.0015	.0015	.0026
Sr.....	1.	1.5	2.	.5	.7	5.	.28
V.....	.0007	.001	.0015	.005	.0015	.015	.012
Y.....	.02	.02	.07	.07	.07	.15	.046
Zr.....	<0.001	<0.001	.0015	.005	<0.001	<0.001	.013
Si.....	.15	.3	.15	.5	.5	.2	6.8
Al.....	.3	.07	.07	.3	.1	.1	2.3
Na.....	.15	.3	.2	.15	.15	.15	1.3
K.....	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7	2.6
P.....	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	.6
Ce.....	.05	.15	.3	.5	.5	.7	.53
Yb.....	.0015	.002	.003	.003	.005	.007	.0075
Nd.....	.03	.03	.15	.2	.2	.3	.3
Sm.....	<0.01	<0.01	.03	.07	.07	.07	.05
Eu.....	<0.01	<0.01	.01	<0.01	<0.01	.015	.055
Gd.....	<0.005	<0.005	<0.005	.015	.02	.03	N.D.
Tb.....	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	N.D.
Dy.....	<0.005	<0.005	.015	.015	.015	.02	N.D.
Ho.....	<0.002	<0.002	.005	<0.002	<0.002	.007	N.D.
Er.....	<0.005	<0.005	.007	<0.005	.007	.015	N.D.
ΣLREE <sub>2</sub> ..	.13	.25	.643	.97	.97	1.385	1.53
ΣHREE ..	.0215	.022	.1	.103	.117	.229	.085
Gamma ray spectrometric analyses (in parts per million)							
RaeU <sup>3</sup> ..	0.4	0.6	6.69	1.2	4.5	2.7	26.
Th.....	14.	23.2	245.	224.	247.	250.	1500.

<sup>1</sup>ΣLREE--total light rare-earth and related elements: La+Ce+Nd+Sm+Eu.

<sup>2</sup>ΣHREE--total heavy rare-earth elements: Y+Yb+Gd+Tb+Dy+Ho+Er.

<sup>3</sup>RaeU--radium-equivalent uranium.

TABLE 6.—*Mineralogy of carbonatites in diamond drill core from Gem Park, Wet Mountains area, Colorado*

[From Papson (1981, p. 18). C, common; M, moderately common; R, rare; VR, very rare]

Mineral	Formula	Abundance
Albite (low) ..	NaAlSi <sub>3</sub> O <sub>8</sub> .....	R
Ancylite.....	SrCe(CO <sub>3</sub> ) <sub>2</sub> (OH)·H <sub>2</sub> O.....	VR
Ankerite.....	Ca(Fe <sup>+2</sup> ,Mg,Mn)(CO <sub>3</sub> ) <sub>2</sub> .....	R
Barite.....	BaSO <sub>4</sub> .....	R
Bastnaesite...	(Ce,La)(CO <sub>3</sub> )F.....	R
Bornite.....	Cu <sub>5</sub> FeS <sub>4</sub> .....	VR
Calcite.....	CaCO <sub>3</sub> .....	M
Celestite.....	SrSO <sub>4</sub> .....	R
Chalcopyrite..	CuFeS <sub>2</sub> .....	M
Dolomite.....	CaMg(CO <sub>3</sub> ) <sub>2</sub> .....	C
Edenite.....	NaCa <sub>2</sub> (Mg,Fe <sup>+2</sup> ) <sub>5</sub> Si <sub>7</sub> AlO <sub>22</sub> (OH) <sub>2</sub> ...	C
Fluorapatite..	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F.....	C
Fluorite.....	CaF <sub>2</sub> .....	R
Hematite.....	α-Fe <sub>2</sub> O <sub>3</sub> .....	M
Lamprophyllite	Na <sub>2</sub> (Sr,Ba) <sub>2</sub> Ti <sub>3</sub> (SiO <sub>4</sub> ) <sub>4</sub> (OH,F) <sub>2</sub> ....	R
Magnetite.....	Fe <sup>+2</sup> Fe <sup>+3</sup> <sub>2</sub> O <sub>4</sub> .....	C
Marcasite.....	FeS <sub>2</sub> .....	VR
Monazite.....	(Ce,La,Nd,Th)PO <sub>4</sub> .....	R
Phlogopite....	KMg <sub>3</sub> Si <sub>3</sub> AlO <sub>10</sub> (F,OH) <sub>2</sub> .....	C
Pyrochlore....	(Na,Ca) <sub>2</sub> Nb <sub>2</sub> O <sub>6</sub> (OH,F).....	C
Pyrite.....	FeS <sub>2</sub> .....	C
Pyrrhotite....	Fe <sub>1-x</sub> S.....	R
Quartz.....	SiO <sub>2</sub> .....	VR
Siderite.....	FeCO <sub>3</sub> .....	VR
Sphalerite....	ZnS.....	VR
Strontianite..	SrCO <sub>3</sub> .....	R
Zircon.....	ZrSiO <sub>4</sub> .....	C

significant since no such concentrations have been reported in previous studies of the Gem Park Complex. Anomalous values of copper (mean=49 ppm) are also found. The intermediate carbonatite type is characterized by the presence of calcite, monazite, hematite, pyrite, bastnaesite, and low albite. This type has much more rare earths (mean >3.35 percent) than the oldest type, and three times as much niobium (mean=1,754 ppm). Copper values are about the same as the oldest type, but the uranium content is substantially less

(highest value=3 ppm). Although of higher grade for niobium and rare-earth elements, this type occurs principally in small dikes. Larger masses of this carbonatite may occur elsewhere within the complex and could prove a potential source for these elements. The youngest carbonatite type occurs in dikes containing calcite, barite, and strontianite with accessory celestite, ancylite, and rhabdophane. It shows further enrichment in the rare-earth elements (mean >5.23 percent ΣREE) but much less niobium (mean=190 ppm). Copper is about the same as the two older types, but uranium is negligible. Addition of sulfate in this youngest type is indicated by barite and celestite in the carbonatites and a gypsum stockwork within the host gabbro.

## ISOTOPIC RATIOS

Primary magmatic and replacement carbonatites in the Wet Mountains area form two distinct petrographic groups that also differ in their mineralogical and geochemical characteristics. These differences suggest the possibility of different origins for the two groups—perhaps the replacement carbonatites are hydrothermal, and the fluids transporting the carbonate and other components were derived from a source completely unlike that of the primary magmatic carbonatites. With this possibility in mind, several samples of primary magmatic and replacement carbonatites were analyzed for their oxygen and carbon isotopic contents by R.O. Rye (written commun., 1977) and by Irving Friedman (written commun., 1965), both of the U.S. Geological Survey. The results appear in table 9.

According to Deines and Gold (1973), the average δ<sup>13</sup>C value for a large number of carbonatites is -5.1 per mil (s=±1.4 per mil). This value is indistinguishable from values found in carbonates of kimberlite pipes and in diamond, indicating a deep-seated origin. The value for marine carbonates is near 0 per mil (Rye and Ohmoto, 1974). The δ<sup>13</sup>C values for Wet Mountains primary magmatic and replacement carbonatites are nearly identical to one another and also indicate that the carbon had a deep-seated origin. If the replacement carbonatites have a hydrothermal origin, exchange of isotopes with other carbon reservoirs has not occurred to any great extent and changes in δ<sup>13</sup>C due to variations in f<sub>O<sub>2</sub></sub>, temperature, and other factors as shown by hydrothermal systems (Rye and Ohmoto, 1974) also have not occurred.

Primary unaltered igneous rocks typically have δ<sup>18</sup>O values between +5.5 and +10.0 per mil (H. P. Taylor, Jr., 1974, p. 859) and δ<sup>18</sup>O for Wet Mountains carbonatites fall in that range (table 9). Interaction with meteoric ground water (δ<sup>18</sup>O for temperate fresh

TABLE 7.—Modal analyses, in volume percent, of 29 carbonatites in diamond drill cores from Gem Park, Wet Mountains area, Colorado

[From Papson (1981, p. 19). Leaders (---), no analyses. X, present in amounts less than 1 percent]

Mineral	Sample Numbers														
	17-77.5	17-222.4	17-276.1	17-280.5	17-296.5	17-350.5	17-353.4	17-355.8	17-366	17-376.5	17-406.3	17-411.3	17-425.4	17-434.5	17-450
Dolomite.....	51.2	31.4	51.2	21.5	27.5	51.5	23.3	59.4	39.2	85.7	60.8	23.7	79.9	80.4	26.4
Apatite.....	33.7	39.6	19.4	54.5	32.8	39.2	41.0	20.3	39.8	5.9	8.3	42.0	4.4	0.2	44.5
Fluorite.....	---	8.4	0.7	---	---	---	---	20.3	7.3	---	---	---	0.3	0.2	0.8
Phlogopite (fresh).....	---	15.3	---	6.8	4.6	2.0	---	---	8.1	---	5.3	---	---	---	24.2
Phlogopite (altered)....	---	---	2.8	3.2	15.4	9.3	---	---	---	5.8	20.1	---	11.8	11.7	---
Pyrochlore.....	---	2.1	---	0.4	1.6	0.3	1.7	---	0.5	0.4	---	---	---	0.4	---
Zircon.....	---	3.1	---	---	---	---	---	---	X	---	---	---	---	---	---
Pyrite.....	1.3	X	12.7	0.4	X	X	4.0	---	---	---	12.3	0.8	X	1.0	---
Magnetite.....	---	X	6.5	8.6	16.9	0.1	20.5	---	3.3	1.8	6.8	0.7	2.4	0.5	2.3
Hematite.....	8.1	---	---	4.6	0.2	---	---	---	---	---	X	10.5	---	---	X
Chalcopyrite...	---	X	---	---	---	---	---	---	---	---	---	---	---	---	---
Calcite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Bastnaesite....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Monazite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Albite (low)...	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Strontianite...	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Ancylite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Others.....	5.7	0.1	6.7	---	1.0	6.9	0.2	---	1.8	0.4	6.5	2.2	1.2	5.6	1.8
Points counted	1230	1854	1466	1508	1336	1404	1419	1340	1931	1522	1464	1462	1485	1725	1449

Mineral	Sample Numbers														
	17-499	17-504.3	17-515.9	17-537.5	17-541.2A	17-541.2B	17-570.5	39-7	39-80	39-88	39-102	39-117	35-544.7	35-618	35-783.4
Dolomite.....	79.0	74.3	39.8	22.0	38.1	28.1	54.2	22.1	40.9	70.7	76.6	26.6	5.4	39.2	10.3
Apatite.....	1.1	7.6	10.3	36.9	25.0	50.0	10.1	---	29.3	---	---	27.1	13.6	9.9	---
Fluorite.....	0.1	3.7	X	---	0.6	---	3.1	---	---	---	---	---	---	---	---
Phlogopite (fresh).....	---	0.2	X	3.2	5.4	8.8	25.0	---	---	---	---	---	39.8	---	---
Phlogopite (altered).....	4.9	7.1	2.2	---	---	---	---	---	---	---	---	1.2	---	---	---
Pyrochlore.....	0.8	0.3	0.3	1.8	1.4	2.8	1.9	---	---	3.4	---	---	---	---	---
Zircon.....	---	0.1	0.4	0.3	1.0	---	---	---	---	---	---	---	---	---	---
Pyrite.....	X	---	---	12.5	6.5	---	---	---	---	---	---	---	---	---	---
Magnetite.....	6.6	3.9	43.7	11.9	8.0	1.2	0.1	---	---	---	---	---	---	---	---
Hematite.....	X	---	---	---	X	---	---	---	---	4.8	3.2	---	---	---	---
Chalcopyrite...	---	---	---	---	X	0.1	---	---	---	---	---	---	---	---	---
Calcite.....	---	---	---	---	---	---	---	59.3	---	---	---	41.8	---	32.7	25.1
Bastnaesite....	---	---	---	---	---	---	---	---	7.0	5.4	2.6	1.2	---	---	6.2
Monazite.....	---	---	---	---	---	---	---	13.8	---	1.4	4.6	2.1	12.1	10.1	0.3
Albite (low)...	---	---	---	---	---	---	---	4.1	19.7	14.3	11.9	---	---	---	---
Strontianite...	---	---	---	---	---	---	---	---	---	---	---	---	29.1	---	28.4
Ancylite.....	---	---	---	---	---	---	---	---	---	---	---	---	---	---	29.7
Others.....	7.5	2.9	3.6	23.8	8.7	1.5	5.6	0.7	3.1	---	1.1	---	---	8.1	---
Points counted	1436	1303	1959	1641	1977	2000	1350	1450	1461	1176	1512	1455	1079	1213	1300

TABLE 8.—Summary of geochemical data from carbonatites in diamond drill core from Gem Park, Wet Mountains area, Colorado

[Data are in percent. ΣREE, total rare-earth elements; N.D., no data. Data and drill-hole locations from Papson (1981)]

Element	Average of 29 Gem Park samples	Drill Hole No. GP-17 (21 samples)	Drill Hole No. GP-35 (3 samples)	Drill Hole No. GP-39 (5 samples)	Average composition of carbonatites (Gold, 1963)
Fe.....	5.89	>6.52	2.667	5.2	5.12
Mg.....	4.95	5.48	2.833	4.0	3.40
Ca.....	>10.0	>10.0	>10.0	>10.0	25.10
Ti.....	0.083	0.078	0.008	0.148	0.48
Mn.....	0.314	0.281	0.3	0.46	0.47
Ba.....	0.328	0.0128	2.833	0.15	0.23
Co.....	0.0038	0.0035	0.002	0.0061	0.0017
Cr.....	0.0015	0.001	0.004	0.0021	0.0048
Cu.....	0.005	0.0049	0.006	0.0046	0.00025
La.....	>0.519	0.0888	>2.0	>1.44	0.0516
Nb.....	0.074	0.0584	0.019	0.1754	0.1951
Ni.....	0.0014	0.0011	N.D.	0.0032	0.0008
Pb.....	0.0014	0.0005	0.007	0.0016	N.D.
Sc.....	0.0021	0.0025	N.D.	0.0016	0.001
Sr.....	>2.31	1.619	>10.0	0.59	0.34
V.....	0.0088	0.0087	N.D.	0.0144	N.D.
Y.....	0.015	0.0164	0.0133	0.013	0.0096
Zr.....	0.0425	0.058	0.0007	0.0036	0.112
Si.....	0.731	0.764	0.35	0.82	5.66
Al.....	0.179	0.111	0.25	0.41	1.88
Na.....	0.384	0.302	0.667	0.56	0.31
K.....	0.576	0.262	1.67	1.24	1.24
P.....	2.84	3.476	1.5	1.0	0.90
Ce.....	>0.522	0.14	2.0	>1.24	0.15
Ga.....	0.0006	0.0006	0.0002	0.0007	0.0001
Yb.....	0.0007	0.0008	0.0008	0.0004	N.D.
Na.....	0.259	0.0821	1.067	0.52	N.D.
Th.....	0.0104	0.0067	0.0292	0.0146	N.D.
U.....	0.0018	0.00247	0.00002	0.001	N.D.
ΣREE .....	>1.39	0.3713	>5.226	>3.3468	N.D.

waters = -10 to -4 per mil; Taylor and others, 1967) or other nonigneous reservoirs of oxygen ( $\delta^{18}\text{O}$  for marine limestone = +22 to +30 per mil; Taylor and others, 1967), appears to be minimal.

In figure 2, the  $\delta^{13}\text{C}$  values for the carbonatites are plotted against  $\delta^{18}\text{O}$  and compared with the field of PIC (primary igneous carbonatites) established by Taylor and others (1967). Two analyses of Iron Hill,

Colo., primary magmatic carbonatite (Taylor and others, 1967) are also included for comparison. Values for Wet Mountains carbonatites plot near or just inside the field of PIC and are bracketed by values from the Iron Hill carbonatite. According to Taylor and others (1967),  $\delta^{18}\text{O}$  values higher than those in the field of PIC, which are the same as primary magmatic carbonatites, may reflect late stage and secondary exchange

TABLE 9.—Oxygen and carbon isotopic compositions of carbonatites from the Wet Mountains area, Colorado

[Data are in ‰ (per mil). SMOW, standard mean ocean water standard; PDB, Pee Dee belemnite standard. Analyses of WM-samples by Irving Friedman, analyses of remainder of samples by R.O. Rye, both of the U.S. Geological Survey]

Sample No.	$\delta^{18}\text{O}$ (SMOW)	$\delta^{13}\text{C}$ (PDB)
Primary carbonatite		
8B.....	9.3	-4.8
94B-2.....	10.0	-4.9
WM-24-63...	9.1	-3.2
WM-25-63...	7.1	-4.7
Replacement carbonatite		
106.....	8.3	-4.9
117.....	7.8	-4.9

effects. Sheppard and Dawson (1973) suggested that  $\delta^{13}\text{C}$  values beyond the PIC field may reflect isotopic heterogeneities of the deep-seated source zone. Blattner and Cooper (1974) suggested that it may be necessary to redefine the PIC field as new data become available. However, even if exchanges between carbonatite magma and the Precambrian host terrane did occur, and were sufficient to shift the  $\delta^{18}\text{O}$  values outside the PIC field, the shift in the  $\delta^{13}\text{C}$  values was not due to any such exchanges, because carbonate rocks are scarce in the Precambrian terrane. The ubiquitous fenitization offers the possibility of some  $\delta^{18}\text{O}$  exchange with the host rock, but the effects probably could not be detected because of the similarities in the fields of PIC and of carbon in granitic rocks in figure 2.

### RED SYENITE DIKES

As part of the study of thorium resources in the Wet Mountains area (Armbrustmacher, 1975, 1976; Staatz and others 1979, 1980), a number of anomalously radioactive red syenite dikes were found to contain small reserves of thorium. Red syenite dikes are commonly difficult to distinguish from fenite formed from alteration of granitic rocks adjacent to the alkaline complexes and adjacent to some other types of associated dikes and veins.

The red syenite dikes intrude Early Proterozoic metamorphic rocks, Precambrian intrusive granitic rocks, and rocks of the McClure Mountain and Gem

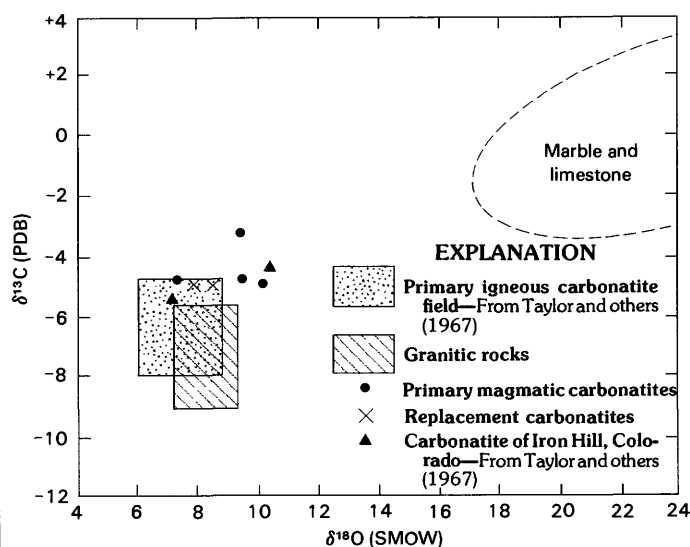


FIGURE 2.—Plot of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data from table 9. Diagram taken from Armbrustmacher (1979).

Park Complexes. No red syenite dikes have been found intruding the syenites at Democrat Creek. This suggests an age between 535 and 511 m.y. However, Olson and others (1977, p. 680) have whole-rock K/Ar dates of  $485 \pm 24$  m.y.,  $560 \pm 28$  m.y., and  $427 \pm 22$  m.y., and whole-rock Rb/Sr isochron of  $495 \pm 10$  m.y. for red syenites from the Wet Mountains area, so the age of the red syenites is uncertain.

According to Heinrich and Moore (1970), the red syenite dikes predate the carbonatite dikes and post-date the lamprophyre dikes. Indeed, a carbonatite dike intersects a red syenite dike and a lamprophyre dike contains red syenite xenoliths, which may have originally been part of a red syenite dike or a fragment of fenitized wall rock. Thus, it would seem that the carbonatites are the youngest dikes and the lamprophyre dikes are the oldest. The quartz-barite-thorite veins postdate red syenite dikes and will be discussed in the following pages.

The red syenites have been intruded along the system of fractures with a predominant northwest strike; most are south of the alkaline intrusive complexes. Some red syenite dikes persist for several kilometers along strike; others are difficult to trace for more than a few meters. Thicknesses are extremely variable but a thickness of about 1 meter is typical. At one locality, where a shaft has been sunk on a red syenite dike, the dike wedges out downward even though the fracture zone containing the dike persists. South of the alkaline intrusive complexes, the country rock is chiefly well-foliated Early Proterozoic metamorphic rocks, and the system of fractures is developed normal to the foliation. North

of the alkaline intrusive complexes, the country rock is chiefly Precambrian intrusive granitic rocks lacking well-developed foliation, and the system of fractures is not nearly as well developed. This same fracture system is occupied by some of the carbonatite dikes, especially replacement carbonatites (Armbrustmacher, 1979), and by quartz-barite-thorite veins. The same fracture that contains a specific dike species or vein at one locality, may contain a different dike species or vein along strike. The same fracture system may have been reused by different intrusive events at slightly different times.

In the field, the red syenite dikes are obvious in outcrop because of their bright-red color. They also tend to be somewhat more resistant to erosion than the surrounding country rocks and stand in slight relief. Their color is caused by finely disseminated grains of red ferric iron oxide contained in the most abundant mineral, potassic feldspar. However, according to Heinrich and Moore (1970), similar-appearing rocks are also found in several different geologic settings in the Wet Mountains area. The similar-appearing rocks occur as dikes and irregular masses replacing granitic and biotitic gneisses, as composite feldspar rock-carbonatite bodies, and as dikes of fine-grained to aphanitic (phaneritic?) and porphyritic trachyte. These rocks probably represent different types of fenite, some in situ, some perhaps rheomorphic. Those rocks called red syenites in this study are not formed by replacement, and all come from dike-like bodies that have sharp, intrusive contacts with the enclosing country rock.

#### MINERALOGY

Heavy-mineral separates were made of a variety of rocks from red syenite dikes. For the most part, the total heavy-mineral fraction of red syenites was sparse compared to that of many other leucocratic rock types.

Many minerals are found in rocks from red syenite dikes; these are listed in table 10. Some of the minerals are primary, but some are part of a later episode of thorium- and rare-earth-element mineralization superimposed upon the red syenite dikes. This later mineralization is probably part of the same event that resulted in quartz-barite-thorite veins, discussed in an ensuing section. As mentioned earlier, the red syenite dikes occupy some of the same fracture zones as quartz-barite-thorite veins, and fairly high levels of radioactivity, due to thorium, occur in some of the red syenite dikes especially at fractured contacts between dike rock and country rock.

The most abundant mineral is potassic feldspar, chiefly microcline. In thin section, the potassic feldspar is turbid to varying degrees due to finely disseminated

ferric iron oxide. Under the Luminoscope<sup>1</sup>, with electron excitation, the potassic feldspar luminesces red, the activator element being ferric iron. This bright-red cathodoluminescence is characteristic of feldspars in fenites (Mariano, 1979) because the fenitizing solutions are enriched in ferric iron as well as alkali metals, and recrystallizing feldspar incorporates the ferric iron into its structure as an impurity. The ferric iron oxide causing the turbidity may also result from exsolution of excess ferric iron oxide in the feldspar structure with changing pressure-temperature conditions as well as from slightly later addition of ferric iron oxide along crystal-structural weaknesses. Determinations of composition and structural states of potassic feldspars by Moore (1969) showed a similarity of these properties between feldspars in fenite zones and feldspars in red syenite dikes. The potassic feldspars are chiefly maximum microclines containing less than 5 mol. percent albite (Moore, 1969, p. 99).

Albite may be fairly abundant in some rocks from red syenite dikes. It displays characteristic albite twinning, and it also may contain abundant finely disseminated ferric iron oxide grains. This sodic feldspar also displays bright-red cathodoluminescence with electron excitation under the Luminoscope. Moore's (1969) studies of compositions and structural state show the albites contain less than 3 mol. percent microcline and are similar to the highly ordered, low-temperature structural type of albite (Moore, 1969, p. 105).

Mafic minerals are rare and include a pleochroic green pyroxene that has all the optical properties of aegirine and of biotite and its alteration product chlorite. The other rock-forming minerals listed in table 10 are chiefly accessory minerals that occur in amounts of less than 1 percent.

The epigenetic minerals (table 10) belong to the episode of thorium mineralization (Christman and others, 1959; Armbrustmacher, 1976, 1981). They are found in the red syenite dikes either along fractures, especially near the contact between dikes and country rocks, or as replacements of the original silicate minerals. Barite replaces potassic feldspar and may become a major constituent of the rock, but it is typically present in highly variable amounts. Calcite and dolomite may also replace potassic feldspar, but typically in amounts less than barite, and they occur as narrow veinlets. Quartz is interstitial to potassic feldspar, and the paragenesis is uncertain—it may be late-stage magmatic or hydrothermal, or it may be both. The rare-earth and thorium minerals are sparse and have been identified by X-ray diffraction techniques. The iron

<sup>1</sup>Nuclide Corp., model ELM-2B. Use of brand or trade names does not constitute endorsement by the U.S. Geological Survey.



TABLE 10.—*Minerals in red syenite dikes in the Wet Mountains area, Colorado*

[Identifications are based on visual inspection and X-ray diffraction techniques. Query (?) means data are insufficient for positive identification]

Rock-forming minerals	Formula	Epigenetic minerals	Formula
Acmite.....	$\text{NaFe}^{+3}\text{Si}_2\text{O}_6$	Barite.....	$\text{BaSO}_4$
Albite.....	$\text{NaAlSi}_3\text{O}_8$	Bastnaesite(?)...	$(\text{Ce}, \text{La})(\text{CO}_3)\text{F}$
Anatase.....	$\text{TiO}_2$	Brockite.....	$(\text{Ca}, \text{Th}, \text{Ce})(\text{PO}_4) \cdot \text{H}_2\text{O}$
Biotite.....	$\text{K}(\text{Mg}, \text{Fe}^{+2})_3(\text{Al}, \text{Fe}^{+3})\text{Si}_3\text{O}_{10}(\text{OH}, \text{F})_2$	Calcite.....	$\text{CaCO}_3$
Chalcopyrite.....	$\text{CuFeS}_2$	Dolomite.....	$\text{CaMg}(\text{CO}_3)_2$
Chlorite.....	$(\text{Mg}, \text{Al}, \text{Fe})_{12}(\text{Si}, \text{Al})_8\text{O}_{20}(\text{OH})_{16}$	Galena.....	$\text{PbS}$
Fluorapatite.....	$\text{Ca}_5(\text{PO}_4)_3\text{F}$	Goethite.....	$\alpha\text{-Fe}^{+3}\text{O}(\text{OH})$
Fluorite.....	$\text{CaF}_2$	Hematite.....	$\alpha\text{-Fe}_2\text{O}_3$
Potassic feldspar...	$\text{KAlSi}_3\text{O}_8$	Lepidocrocite....	$\gamma\text{-Fe}^{+3}\text{O}(\text{OH})$
Pyrite.....	$\text{FeS}_2$	Quartz.....	$\text{SiO}_2$
Rutile.....	$\text{TiO}_2$	Thorite.....	$\text{ThSiO}_4$
Xenotime.....	$\text{YPO}_4$		
Zircon.....	$\text{ZrSiO}_4$		

oxide minerals and interstitial ferric oxide stain are at least partly products of weathering, but the presence of hydrothermal specular hematite in quartz-barite-thorite veins suggests a hydrothermal genesis for some of the hematite in the red syenite.

#### GEOCHEMISTRY

The mean and range of 46 analyses of rocks from red syenite dikes are given in table 11. For comparison, data for the average igneous rock of the upper continental crust (Wedepohl, 1971, p. 65) are also given.

Rocks from the red syenite dikes contain more than 3 times as much barium, beryllium, lanthanum, niobium, lead, yttrium, zirconium, phosphorus, cerium, ytterbium,  $\Sigma\text{LREE}$ ,  $\Sigma\text{HREE}$ , thorium, and uranium than the average igneous rock (table 11). All these elements, except perhaps phosphorus and zirconium, are probably present in relatively large amounts in the epigenetic minerals (table 10). The minor element content of the red syenites cannot be meaningfully

compared to that of either the hornblende-biotite syenite or the nepheline syenite because of hydrothermal addition of some of these elements to the red syenite. Thus, it is not possible to test the idea that the red syenites may be more highly fractionated products of magmas that produced either of the other syenites. Kinship with Precambrian rocks cannot be tested for the same reasons.

A whole-rock rubidium-strontium isochron of red syenites given by Olson and others (1977, p. 683) yields an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.7048 and a whole-rock date of  $495 \pm 10$  m.y. When compared with initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of other rocks from the Wet Mountains area (Armbrustmacher and Hedge, 1982), the ratio of the red syenite is nearly identical to ratios for a plagioclase-clinopyroxene cumulate (0.70477) at Iron Mountain and for a sample of hornblende-biotite syenite (0.70475) both in the McClure Mountain Complex. This suggests that these rocks have been derived from a similar magmatic source. If the red syenites had been derived from rheomorphic fenites, the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios would be expected to have values nearer that of crustal rocks.

TABLE 11.—*Arithmetic means and ranges of 46 analyses, in percent, of rocks from red syenite dikes in the Wet Mountains area, Colorado*

[Data are in percent. All elements except Th and RaeU determined by semi-quantitative spectrographic analysis; Th and RaeU determined by gamma-ray spectrometric analysis; igneous rocks in the upper continental crust from Wedepohl (1971, p. 65)]

Element	Red syenite		Average igneous rock
	Mean	Range	
Ba.....	0.33	0.003-7.	0.059
Be.....	.0019	<0.0001-0.02	.0002
Co.....	.0006	<0.0005-0.002	.0012
Cr.....	.0029	<0.0001-0.015	.007
Cu.....	.0019	.0001-0.015	.003
La.....	.02	<0.005-0.15	.0044
Mo.....	.0003	<0.0003-0.002	.0001
Nb.....	.022	<0.001-5.	.002
Ni.....	.0015	<0.0005-0.01	.0044
Pb.....	.011	<0.001-1.	.0015
Sc.....	.001	<0.0005-0.005	.0014
Sr.....	.039	.0007-2.	.029
V.....	.0066	<0.0005-0.02	.0095
Y.....	.051	<0.002-0.7	.0034
Zr.....	.058	.0015-0.5	.016
P.....	.27	<0.2-3.	.081
Ce.....	.031	<0.01-0.15	.0075
Ga.....	.003	.001-0.01	.0017
Yb..... <sup>1</sup>	.0041	<0.0002-0.03	.00034
ΣLREE ..	.078	<0.06-0.5	.0165
ΣHREE <sup>2</sup> ..	.077	<0.05-1.	.0059
Th.. <sup>3</sup>	.27	.011-4.	.0011
RaeU ...	.0034	<0.0002-0.04	.00035

<sup>1</sup> ΣLREE, total light rare-earth elements.

<sup>2</sup> ΣHREE, total heavy rare-earth elements.

<sup>3</sup> RaeU, radium-equivalent uranium.

#### QUARTZ-BARITE-THORITE VEINS AND FRACTURE ZONES

Quartz-barite-thorite veins and fracture zones contain the largest resources of thorium in the Wet Mountains area. They form a continuous series ranging from solid quartz-barite-thorite veins at one extreme to fracture zones devoid of obvious megascopic gangue minerals at the other. They most likely would be the first type of deposit to be exploited.

The distribution of vein minerals along strike is irregular and unpredictable, and thus it is difficult to determine how well a sample represents a particular vein. Workings on any vein and fracture zone are not extensive; few underground workings are accessible. Little ore-grade material exists on the dumps, because the ore that was mined was hand sorted.

Quartz-barite-thorite veins and thorium-bearing fracture zones have not been found east of the Ilse fault nor west of the Texas Creek and Westcliffe faults. The northern limit of their outcrop is probably near the Amethyst carbonatite deposit (pl. 1) and the southern limit is probably near the Custer-Huerfano County line. Thorium-bearing veins and fracture zones typically strike normal to the pronounced foliation in the Proterozoic metasedimentary rocks and have a vertical dip. Veins and fracture zones appear to be more abundant south of the alkaline complexes because of the greater abundance of foliated metasedimentary and metavolcanic rocks; the terrain north of the complexes has more of the Proterozoic intrusive igneous rocks that are not foliated. Veins and fracture zones appear to cut across rocks of Proterozoic age and rocks of the alkaline complexes, but no thorium-bearing veins and fracture zones have been found in Tertiary volcanic or sedimentary rocks. Thus, the quartz-barite-thorite veins and fracture zones appear to be products of the youngest event associated with the episode of alkaline magmatism that also produced rocks of the McClure Mountain Complex, Gem Park Complex, the complex at Democrat Creek, and dikes of carbonatite, lamprophyre, and red syenite.

#### MINERALOGY

Two types of minerals have been identified in heavy-mineral separates prepared from rocks from quartz-barite-thorite veins and fracture zones (table 12). One type is made up of epigenetic minerals that were deposited by hydrothermal fluids; the other type is made up of minerals contained in the host rocks of the veins and fracture zones. These minerals are especially abundant in rocks collected from fracture zones where epigenetic minerals are sparse.

The most abundant epigenetic mineral in the thorium-rich veins is smoky quartz. This mineral formed fairly early in the paragenetic sequence and is commonly seen lining the walls of a vein with euhedral, singly terminated crystals projecting from the walls toward the vein interior. At the Little Maude claim (pl. 1), euhedral smoky quartz crystals project into vugs, are stained red, and commonly attain a diameter of 10 cm. The crystal faces are etched, and the crystals are strongly zoned parallel to crystal faces. In thin section, quartz

TABLE 12.—*Mineralogy of quartz-barite-thorite veins and fracture zones in the Wet Mountains area, Colorado*

[Query (?) indicates insufficient data for adequate identification]

Epigenetic minerals	Formula	Host rock minerals	Formula
Ancylite(?).....	$\text{SrCe}(\text{CO}_3)_2(\text{OH}) \cdot \text{H}_2\text{O}$	Acmite.....	$\text{NaFe}^{+3}\text{Si}_2\text{O}_6$
Barite.....	$\text{BaSO}_4$	Anatase.....	$\text{TiO}_2$
Brockite.....	$(\text{Ca}, \text{Th}, \text{Ce})(\text{PO}_4) \cdot \text{H}_2\text{O}$	Biotite.....	$\text{K}(\text{Mg}, \text{Fe}^{+2})_3(\text{Al}, \text{Fe}^{+3})\text{Si}_3\text{O}_{10}(\text{OH}, \text{F})_2$
Calcite.....	$\text{CaCO}_3$	Chlorite.....	$(\text{Mg}, \text{Al}, \text{Fe})_{12}(\text{Si}, \text{Al})_8\text{O}_{20}(\text{OH})_{16}$
Cerussite.....	$\text{PbCO}_3$	Epidote.....	$\text{Ca}_2(\text{Al}, \text{Fe}^{+3})_3(\text{SiO}_4)_3(\text{OH})$
Chalcopyrite.....	$\text{CuFeS}_2$	Garnet.....	$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$
Dolomite.....	$\text{CaMg}(\text{CO}_3)_2$	Ilmenite.....	$\text{Fe}^{+2}\text{TiO}_3$
Fluorapatite.....	$\text{Ca}_5(\text{PO}_4)_3\text{F}$	Magnetite.....	$\text{Fe}^{+2}\text{Fe}^{+3}_2\text{O}_4$
Galena.....	$\text{PbS}$	Muscovite.....	$\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH}, \text{F})_2$
Goethite.....	$\alpha\text{-Fe}^{+3}\text{O}(\text{OH})$	Potassic feldspar.....	$\text{KAl}_2\text{Si}_3\text{O}_8$
Hematite.....	$\alpha\text{-Fe}_2\text{O}_3$	Quartz (clear, milky)...	$\text{SiO}_2$
Jarosite(?).....	$\text{KFe}_3^{+3}(\text{SO}_4)_2(\text{OH})_6$	Rutile.....	$\text{TiO}_2$
Magnesite(?).....	$\text{MnCO}_3$	Sphene.....	$\text{CaTiSiO}_5$
Monazite.....	$(\text{Ce}, \text{La}, \text{Nd}, \text{Th})\text{PO}_4$	Vermiculite.....	$(\text{Mg}, \text{Fe}^{+2}, \text{Al})_3(\text{Al}, \text{Si})_4\text{O}_{10}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$
Potassic feldspar...	$\text{KAlSi}_3\text{O}_8$	Zircon.....	$\text{ZrSiO}_4$
Pyrite.....	$\text{FeS}_2$		
Quartz (smoky).....	$\text{SiO}_2$		
Siderite.....	$\text{FeCO}_3$		
Sphalerite.....	$(\text{Zn}, \text{Fe})\text{S}$		
Synchysite.....	$(\text{Ce}, \text{La})\text{Ca}(\text{CO}_3)_2\text{F}$		
Thorite.....	$\text{ThSiO}_4$		
Xenotime.....	$\text{YPO}_4$		

is seen to contain abundant two-phase fluid inclusions. Detailed studies of one sample of quartz by C.G. Cunningham, Jr. (written commun., 1976), showed a bimodal population of fluid inclusions consisting of low temperature, moderate salinity, two-phase inclusions and moderate temperature,  $\text{CO}_2$ -rich inclusions. The two-phase inclusions have homogenization temperatures

ranging from 118 to 145 °C; the most common temperature is about 125 °C. Salinities range from 8.4 to 15.1 weight percent NaCl equivalent; the most common salinity is near 12 weight percent. The  $\text{CO}_2$ -rich inclusions have partial homogenization behavior to a liquid  $\text{CO}_2$  phase at 27.5 to 29.8 °C. Cunningham stated that most of the  $\text{CO}_2$ -rich inclusions would

homogenize to a vapor phase but final homogenization temperatures were not obtained because of decrepitation above 200 °C. Cunningham also suggested that both the two-phase inclusions and the CO<sub>2</sub>-rich inclusions are primary and may represent effervescence of CO<sub>2</sub>, possibly causing deposition of the quartz and associated ore minerals.

Barite occurs in highly variable amounts in the quartz-barite-thorite veins. It may be the dominant mineral, such as at the Big Chief claims (pl. 1) where the veins were originally prospected for barite, or it may be virtually absent, such as at the Little Maude claim (pl. 1). In veins that have smoky quartz crystals growing from vein walls, the interstices between the quartz crystals are usually filled with barite, indicating that the barite is younger than the smoky quartz in those veins. In other deposits the paragenetic sequence is not so obvious. Barite is chiefly white or pink, but in a few instances it is bright orange. Veins that have a high barite/quartz ratio tend to contain smaller amounts of thorium. Although mineral analyses are not available, the barite appears to be quite pure and may be suitable for some industrial uses, but none of the deposits in the Wet Mountains area appear to contain sufficient tonnages.

Primary hematite is a common constituent of the thorium deposits, but it never exceeds a few percent in abundance. Secondary iron oxides are also fairly abundant. Goethite is generally the most common mineral. Other secondary minerals include hematite and non-crystalline iron and manganese oxides. The presence of primary hematite suggests that the fluids depositing the vein materials had high  $f_{O_2}$  and that deposition occurred within the hematite stability field.

Thorite has a characteristic dark-red color and waxy luster. Generally it is closely associated with the secondary iron oxides and can be most easily identified using X-ray diffraction techniques. At many localities strongly radioactive, bright-red iron-oxide-rich material yields no X-ray diffraction pattern characteristic of thorite until the material is heated for 1 hour at 1,000 °C, which indicates that the thorite is in a metamict form. Thorite is typically highly variable in distribution, both along strike and along dip. Prospect pits were only dug at localities where radioactivity was high, which indicated that thorite was abundant; however, most of the thorite was subsequently removed by hand sorting of the vein material by the prospectors. It was available in large amounts for study and analysis only at the Schwarz Ranch (pl. 1), where thorite-rich material had been stockpiled.

Potassic feldspar is found in variable amounts and may have originated from several different sources. Some potassic feldspar appears to have a hydrothermal

origin and is primarily microcline with abundant disseminated grains of red ferric oxide. This gives the feldspar a distinctive pink to red color. The mineralizing hydrothermal solutions have caused alteration of host rock identical in every respect to fentization immediately adjacent to veins and within fracture zones. The hydrothermal alteration of host rock feldspars produces potassic feldspars indistinguishable from that which crystallized from hydrothermal fluids.

Galena is a common, though sparse constituent of many veins. It appears to be more directly associated with barite than with the other gangue minerals. In a few occurrences it is partly or entirely altered to cerussite. Other sulfide minerals, including sphalerite, chalcopryrite, and pyrite, have been found in heavy-mineral separates of some vein and fracture zone samples, but they are neither common nor abundant.

Several types of carbonate gangue minerals and fluorapatite have been found in various veins and fracture zones. They are not very common nor are they abundant. Their parageneses are uncertain, and it is difficult to determine whether they are related to the thorium ore-forming process.

The thorium- and/or rare-earth-bearing minerals have been identified exclusively by X-ray diffraction techniques. The possibility of additional mineral varieties associated with those identified, but present in trace amounts, is not discounted. Brockite, synchysite, ancylite(?), monazite, and xenotime are chiefly associated with ferric iron oxides, and apparently they form relatively late in the mineral paragenesis. Brockite, the thorium-bearing analog of rhabdophane, was originally first described from the Wet Mountains area (Fisher and Meyrowitz, 1962).

#### GEOCHEMISTRY

Barium, beryllium, lanthanum, lead, yttrium, cerium, ytterbium, and thorium occur in veins and fracture zones in amounts at least eight times greater than that in average igneous rocks (table 13). Copper and niobium are enriched by a factor of four. The  $\Sigma$ LREE and  $\Sigma$ HREE are also considerably more abundant. All of the selected elements occur in anomalous amounts in at least some samples (table 13).

Comparisons of element abundance of the thorium deposits of the Wet Mountains area with other thorium districts is possible only in a general way because of a lack of data. Comparisons based on thorium resources (Staatz and others, 1979, 1980) will be discussed later in this report. Staatz (1974) showed that some common mineralogical and geochemical traits were shared by thorium veins from various U.S. districts. In addition

TABLE 13.—*Arithmetic means and ranges of selected elements in 201 samples of quartz-barite-thorite veins and fracture zones from the Wet Mountains area, Colorado*

[All values in parts per million. Average igneous rock gives abundances of elements in igneous rocks of the upper continental crust as determined by Wedepohl (1971, table 7.3, p. 65). Enrichment factor equals arithmetic mean/average igneous rock. Leaders (---) indicate insufficient data]

Element	Mean	Range	Average igneous rock	Enrichment factor
Ba.....	51,615	70->100,000	590	87
Be.....	21	1.5-500	2	10
Co.....	17	<2-100	12	1.4
Cr.....	86	<1-1,500	70	1.2
Cu.....	125	<1-3,000	30	4
La.....	381	<30->30,000	44	9
Nb.....	81	<7-2,000	20	4
Ni.....	71	<5-1,500	44	1.6
Pb.....	2,902	<10-100,000	15	194
Sc.....	22	<3-300	14	1.6
Sr.....	635	<5-7,000	290	2.2
V.....	139	<5-7,000	290	0.5
Y.....	788	<10->20,000	34	23
Zr.....	310	<10-7,000	160	1.9
Ce.....	608	<100-20,000	75	8
Ga.....	12	<5-70	17	0.7
Yb.....	77	<1-3,000	3.4	23
<sup>1</sup> ΣLREE..	1,760	0-58,650	164.6	11
<sup>2</sup> ΣHREE..	1,191	0-47,600	60.1	20
Th.....	4,042	0-67,652	11	368
RaeU... <sup>3</sup>	(*)	<5-360	3.5	---

<sup>1</sup>Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.

<sup>2</sup>Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

<sup>3</sup>Radium-equivalent uranium.

\*Values were obtained for only 27 percent of the samples because the U photopeaks in the rest were obscured by those of Th.

to thorium, the rare-earth elements, barium, copper, and lead appear to be fairly common constituents of thorium veins. If better analytical data were available, niobium would probably also be found to be a characteristic constituent of many thorium veins.

#### SELECTED VEIN-FRACTURE ZONE OCCURRENCES

The detailed mapping and sampling done for this study and for previous studies focused on the most important thorium deposits—those most likely to be worked if economic conditions warranted. The following text discusses five of these deposits.

#### HAPUTA RANCH AREA

The Haputa Ranch area (near lat 38°08'45" N., long 105°16'15" W.) is reported to be the site at which

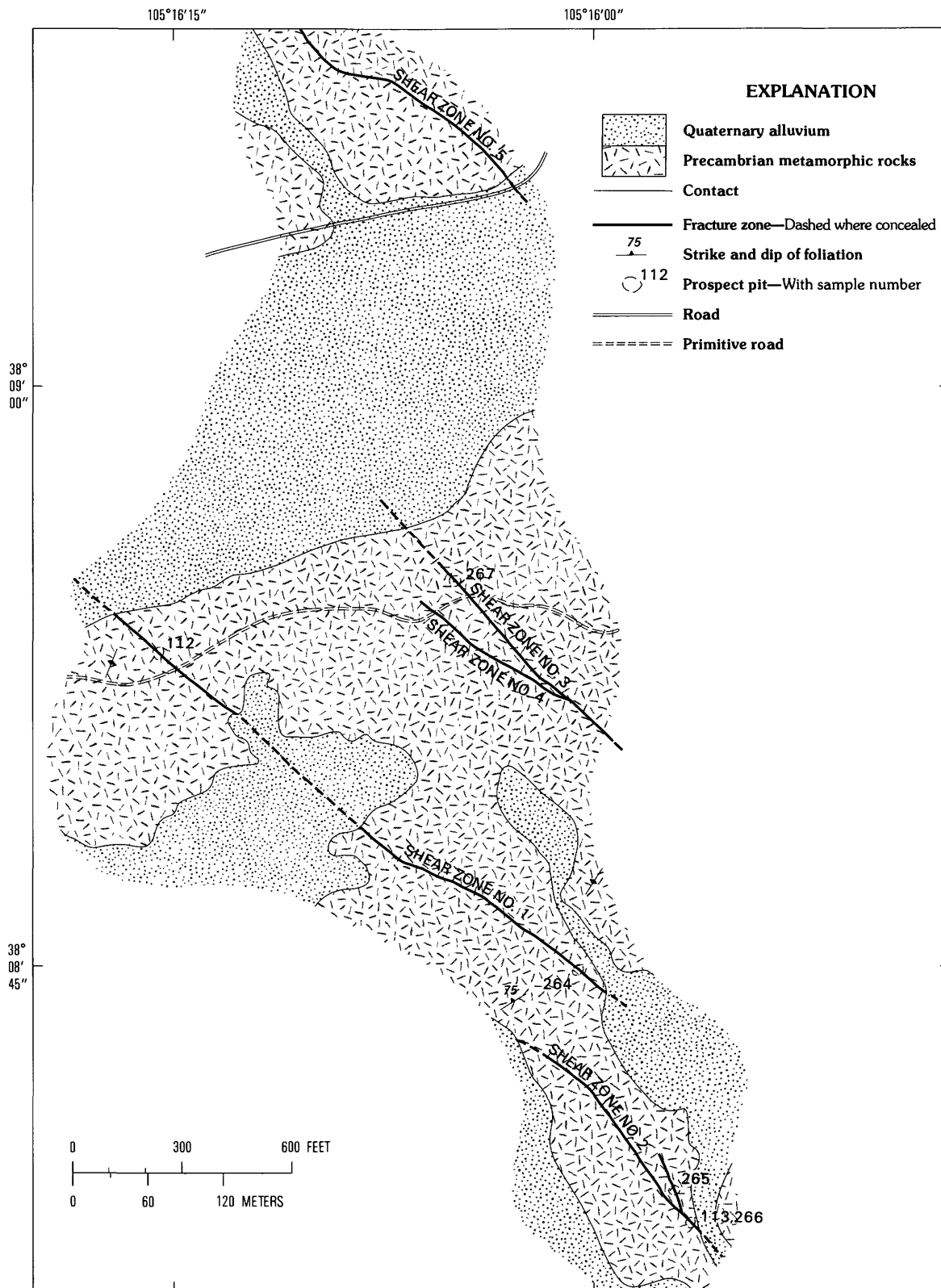
radioactive minerals were first discovered in the Wet Mountains area (Christman and others, 1953). Earlier reports (Christman and others, 1953; Christman and others, 1959) discussed the results of a surface sampling program by the U.S. Geological Survey and a diamond-drilling project by the U.S. Bureau of Mines conducted during 1950-52. For the current study, additional samples were collected from some of the same localities for chemical and mineralogical studies.

The thorium deposits at the Haputa Ranch consist of several en echelon, branching fracture zones (fig. 3), three of which have been extensively explored by dozer cuts and diamond drilling. Although the fracture zones are as wide as 8 m, the strongly radioactive parts seldom exceed about 1 m. Similar structures occur on strike with these fracture zones across alluvial valleys toward the northwest and southeast. The near-vertical fracture zones cut the foliation of the host Proterozoic granitic gneisses and amphibolite at nearly right angles. In places they are closely associated with altered mafic dikes; both probably occurred along the same fracture system. Within the fracture zone, the granitic gneisses are altered and replaced by iron-oxide-bearing potassic feldspar. This altered rock emits a fetid odor when struck with a hammer. Lenses of amphibolite host rock are also altered to vermiculite, and a few excavations were dug by prospectors to determine the quality of the vermiculite.

The fracture zones contain younger, more or less unfractured veins rarely exceeding about 10 cm in thickness. Some of the veins predominantly contain barite; some predominantly contain quartz. Other minerals in the veins and fracture zones include both specular and earthy hematite, galena, and thorite; potassic feldspar, rutile, zircon, magnetite, and an altered mica occur in the fenitized host rock within the fracture zone. The fracture zones are strongly oxidized and altered; therefore, recovery and identification of mineral species is somewhat hindered.

Partial chemical analyses of 10 samples of fracture zones and veins from the Haputa Ranch area are given in table 14. The Haputa Ranch deposits contain considerably more niobium, yttrium, ytterbium, and ΣHREE than the mean values for all vein samples and fracture zones in the Wet Mountains area (table 13). In addition, the ΣLREE to ΣHREE ratio, which is typically greater than 1, reflects the atypical abundance of heavy rare-earth elements relative to light rare-earth elements. The lack of identifiable rare-earth minerals in the veins and fracture zones hampers attempts to explain the anomalous rare-earth distribution in these rocks.

Shear zone no. 1 (fig. 3) averages 0.608 percent ThO<sub>2</sub> based on the analytical data from surface and drill hole



Geology modified from  
Christman and others, 1953

FIGURE 3.—Geologic map and sample localities of thorium deposits at the Haputa Ranch, Wet Mountains area, Colorado.  
Location shown on plate 1.

TABLE 14.—*Abundance of selected elements in samples from fracture zones in the Haputa Ranch area, Wet Mountains area, Colorado*

[Sample localities shown on plate 1 and figure 3. Arithmetic means calculated by replacing >20,000 with 30,000, >10,000 with 15,000, and <50 with 30. Enrichment factor equals arithmetic mean/average igneous rock. Analyses for Th by C.M. Bunker and C.A. Bush, all other analyses by H.G. Neiman and N.M. Conklin]

Element	Sample No.										Arithmetic mean	Enrichment factor
	112	113A	113B	263A	263B	264A	264B	265	266	267		
Ba.....	>20,000	20,000	50,000	50,000	>20,000	20,000	70,000	20,000	300	>20,000	68,030	115
Be.....	50	15	7	30	10	20	15	200	7	5	36	18
Co.....	10	15	20	30	15	30	15	70	30	15	25	2
Cr.....	70	70	50	700	70	150	150	300	70	150	178	3
Cu.....	50	100	50	150	70	150	30	300	70	150	112	4
La.....	30	70	50	150	70	300	70	70	1500	150	246	6
Nb.....	150	200	150	2,000	300	500	700	70	30	300	440	22
Ni.....	50	70	50	200	70	150	30	150	70	30	87	2
Pb.....	200	3,000	1,000	2,000	300	3,000	700	3,000	150	3,000	1,635	109
Sc.....	15	30	15	150	20	70	70	70	20	20	48	3
Sr.....	1,500	300	700	500	1,500	500	700	300	300	700	700	7
V.....	150	200	150	1,500	150	300	200	500	150	300	360	2
Y.....	1,500	5,000	1,500	>10,000	5,000	10,000	1,500	300	500	1,500	4,180	123
Zr.....	200	500	200	1,500	300	700	500	300	150	30	438	3
Ce.....	<50	150	<50	300	150	700	150	150	3,000	500	530	7
Ga.....	15	20	15	70	30	70	50	30	50	30	38	2
Yb.....	70	300	100	3,000	700	1,000	150	15	50	150	554	163
<sup>1</sup> ELREE...	80	470	120	3,100	370	2,000	370	320	7,000	950	1,478	9
<sup>2</sup> EHREE...	1,905	6,360	1,930	47,600	7,990	14,100	2,320	535	700	2,370	8,581	143
Th.....	1,630	14,500	2,170	6,350	2,700	23,000	1,069	2,050	13,200	1,880	6,855	623

<sup>1</sup>Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.

<sup>2</sup>Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

## SAMPLE DESCRIPTIONS

112. Barite vein within fracture zone.  
 113A. High-grade sample collected near NE-corner of dozer cut; dark red to black vein material in fracture zone.  
 113B. Composite sample across 1-m-wide fracture zone.  
 263A. Composite sample across 1-m-wide fracture zone.  
 263B. Composite sample across 1-m-wide fracture zone 0.5 m from 263A in same zone.  
 264A. Dark gray, 5-cm-wide vein in fracture zone.  
 264B. Composite sample across 2-m-wide fracture zone.  
 265. Small, anomalously radioactive dump beside incline sunk for vermiculite.  
 266. Composite sample from radioactive dump.  
 267. Composite sample from vein material in dump.

samples given by Christman and others (1953) and new analytical data in table 14. The zone is 1,765 feet long,<sup>2</sup> averages 12.5 feet wide, and is known from the drilling to persist to an average depth of 277 feet. It is assumed that there are 12 ft<sup>3</sup> per ton of ore material. Shear zone no. 1 thus contains reserves of 3,100 tons of ThO<sub>2</sub>. Shear zone no. 2 is 700 feet long, 5 feet wide, and at least 125 feet deep. This shear zone averages 0.51 percent ThO<sub>2</sub> and this zone thus could yield 185 tons of ThO<sub>2</sub>. Shear zones no. 3 and 4 are 925 feet long, 2.5 feet wide, and 225 feet deep. Samples average 0.077 percent ThO<sub>2</sub> yielding about 33 tons of ThO<sub>2</sub>. Shear zone no. 5 is 775 feet long, about 2 feet wide, and 125 feet deep. It averages only about 0.056 percent ThO<sub>2</sub> yielding less than 10 tons of ThO<sub>2</sub>. In summary, the shear zones at the Haputa Ranch contain reserves of about 3,325 tons of ThO<sub>2</sub>.

<sup>2</sup>Inch-pound units are preferred to SI units in reserve calculations.

## TUTTLE (OR LEPLEY) RANCH AREA

The Tuttle Ranch (owned by Ed Lepley in 1975) is located near lat 38°16'19" N., long 105°18'53" W. Radioactive deposits were first detected here in 1950 by G.B. Gott and L.F. Dellwig (Christman and others, 1953). These deposits have been sampled only at shallow prospect pits and dozer cuts; no drilling has been done.

The veins and fracture zones (fig. 4) cut across the Precambrian layered gneisses, migmatites, and amphibolites at nearly right angles to their predominant northeast foliation. Most of the veins are 1 m thick or less, and all have a vertical dip. Strike of the major shear zone at the Tuttle (Lepley) Ranch is about N. 45° W.

The chief radioactive mineral in the vein-fracture zones is thorite; no other thorium-bearing mineral has been identified. The principal gangue mineral is quartz: clear, euhedral quartz is followed paragenetically by euhedral, smoky quartz and/or red-stained quartz.

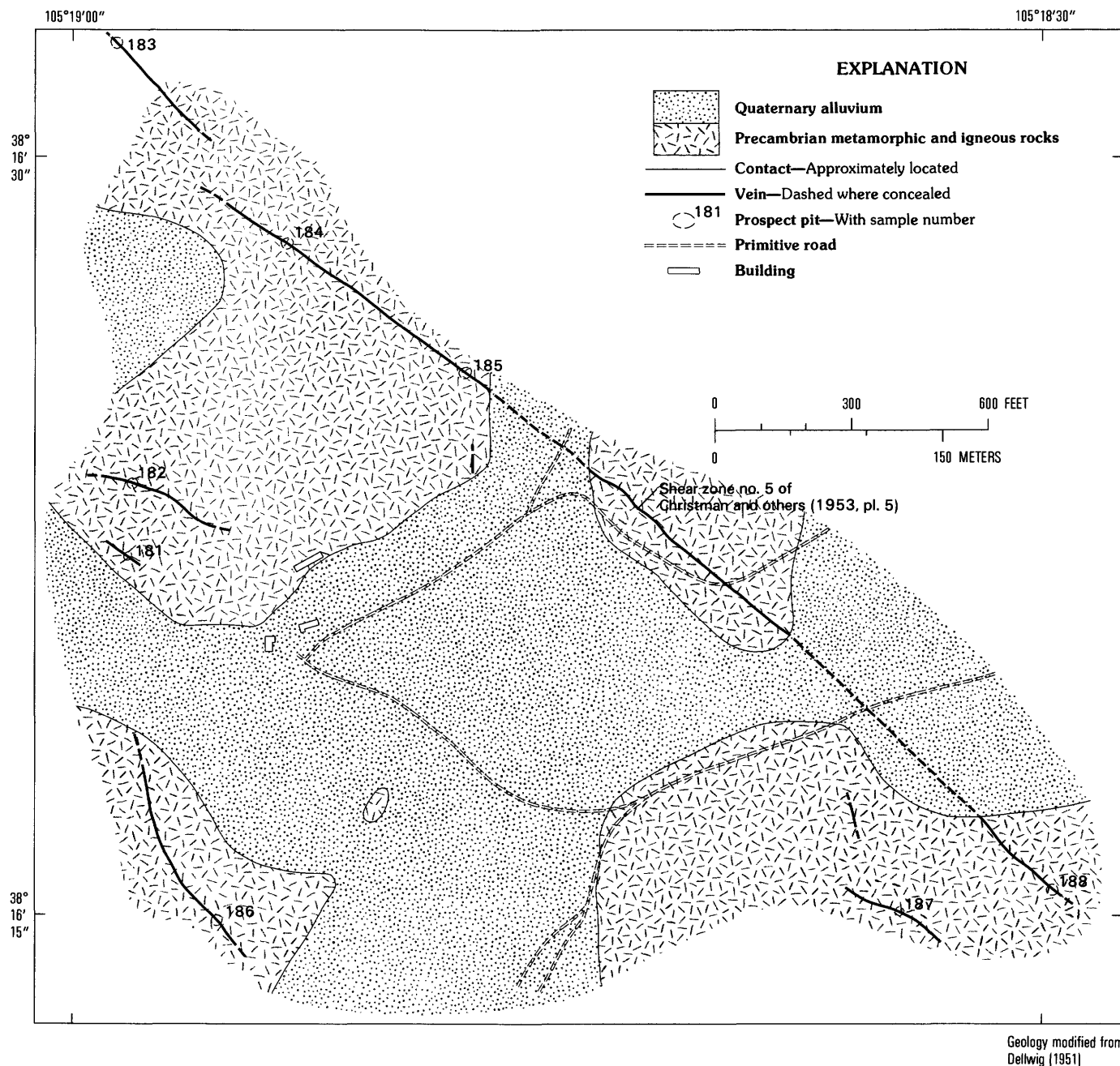


FIGURE 4.—Geologic map and sample localities of thorium deposits at the Tuttle (Lepley) Ranch, Wet Mountains area, Colorado. Location shown on plate 1.

Other vein minerals include colorless and pink barite, calcite, specular hematite, pyrite, goethite, and rutile. Minerals identified in the samples that are probably part of the altered country rock include pink potassic feldspar, quartz, biotite, garnet, and zircon.

Thorium abundances in the samples (table 15) range from about 38 to almost 20,000 parts per million (table 16). The average thorium abundance of the Tuttle

(Lepley) Ranch area is about 15 percent greater than the average thorium abundance in the total samples from veins and fracture zones in the entire Wet Mountains area (table 13). Comparing enrichment factors of the samples at the Tuttle (Lepley) Ranch with enrichment factors of the total samples, it can be seen that Tuttle (Lepley) rocks contain considerably less average lead and barium. Beryllium, zirconium, and thorium are



TABLE 15.—Abundance of selected elements in samples from veins and fracture zones in the Tuttle (Lepley) Ranch area, Wet Mountains area, Colorado

[Sample localities shown on plate 1 and figure 4. Enrichment factor equals arithmetic mean/average igneous rock. Arithmetic means calculated by replacing >10,000 with 15,000, <2 with 1.5, <20 with 15, <100 with 70, and <5 with 3. Analyses for Th by C.M. Bunker and C.A. Bush; all other analyses by L.A. Bradley. N, not detected]

Element	Sample No.									Arithmetic mean	Enrichment factor
	181	182	183	184	185	186	187	188B	188C		
Ba.....	1000	>10,000	1500	1500	3000	>10,000	7000	700	1000	5078	14
Be.....	5	1	50	1	20	200	50	30	15	41	20
Co.....	15	<2	2	5	15	7	7	30	7	10	.8
Cr.....	30	2	30	30	70	20	30	150	30	44	.6
Cu.....	30	30	7	70	70	70	15	300	100	77	3
La.....	70	<20	N	70	300	300	100	300	500	187	4
Nb.....	70	<5	7	150	150	30	70	300	100	98	5
Ni.....	15	<2	10	10	15	30	7	200	20	34	.8
Pb.....	100	200	15	150	500	50	100	70	150	156	10
Sc.....	5	<2	10	7	15	10	10	10	10	9	.6
Sr.....	30	2000	100	300	500	2000	500	200	500	681	2
V.....	70	5	70	70	1500	50	50	150	50	224	2
Y.....	50	<5	50	5000	700	500	200	100	500	789	23
Zr.....	200	<5	150	500	300	150	1500	700	5000	945	6
Ce.....	150	<100	<100	300	500	500	200	300	700	317	4
Ga.....	10	<2	<2	20	30	<2	30	30	20	16	.9
<sup>1</sup> ΣLREE...	320	N	N	670	1100	1250	550	800	1700	710	4
<sup>2</sup> ΣHREE...	57	N	55	6080	1200	860	490	230	157	1014	17
Th.....	547.3	38.5	1764	548.7	19600	2350	5950	2237	9300	4704	428

<sup>1</sup>Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.

<sup>2</sup>Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

## SAMPLE DESCRIPTIONS

181. Fracture zone 1 m thick partly cemented by clear, vuggy quartz.  
 182. Vein, 0.5 m thick; contains barite, pink potassic feldspar, maroon iron oxide.  
 183. Fracture zone, 1 m thick with 2 cm thick quartz vein.  
 184. Vein, 1 m thick; contains quartz, pink potassic feldspar, reddish brown iron oxide.  
 185. Vein, 1 m thick; contains quartz, pink potassic feldspar.  
 186. Vein sample from dump; consists of barite and maroon iron oxide.  
 187. Vein sample from dump; contains abundant feldspar, iron oxide.  
 188B. Fracture zone 1.5 m thick containing abundant clayey gouge.  
 188C. Fracture zone material on dump, rich in iron oxide.

somewhat more abundant. Although the average ΣLREE to ΣHREE ratio is less than 1.0, more than half the samples have a ΣLREE to ΣHREE ratio greater than 1; that is the ΣHREE are more enriched than ΣLREE.

The most prominent structure at the Tuttle (Lepley) Ranch, termed shear zone no. 5 by Christman and others (1953, pl. 5), is about 2,700 feet long, averages about 3 feet wide, and, based on drilling information from the Haputa Ranch deposits, is assumed to continue essentially unchanged to a depth of 250 feet. The average thorium abundance, based on eleven analyses, is 0.69 percent ThO<sub>2</sub>. These data yield reserves of

1,165 tons ThO<sub>2</sub> in shear zone no. 5. The other shear zones combined yield about 125 tons ThO<sub>2</sub>.

## BEARDSLEY DEPOSIT

The Beardsley deposit is located near the southwest corner of the Haputa Ranch property at lat 38°07'30" N. and long 105°18'30" W. It is one of the few deposits that has been developed underground, although the underground workings are not extensive and caving has made the workings inaccessible. In addition to collecting samples from exposures of the vein, radioactivity

measurements were made with a scintillation counter across a dozed area over the deposit in order to delineate the extent of anomalous radioactivity (fig. 5). Background measurements were made over unmineralized granitic gneiss host rock and averaged 270 counts per second.

The Beardsley deposit consists of a strongly radioactive zone of fenitized granitic gneiss up to 8 m wide surrounding several narrow en echelon zones 0.5 m wide that contain abundant vein minerals in thin veinlets. The structure strikes N. 35–40° W. and appears to dip nearly vertically. Bedrock away from the immediate vicinity of the dozed area is poorly exposed.

Narrow radioactive veins contain abundant potassic feldspar, along with smoky quartz and barite. Other minerals include hematite, goethite, cerussite, and brockite(?). Table 16 gives the results of analyses of one sample (79A) taken from a mineralized fracture zone of the Beardsley deposit. The fracture zone contains small veins of quartz, barite, and thorite. Sample 79A contained anomalous amounts of barium, lanthanum, lead, yttrium, cerium,  $\Sigma$ LREE,  $\Sigma$ HREE, and thorium (table 16).

The Beardsley deposit is about 500 feet long, averages about 15 feet wide, and persists for about 250 feet vertically. Using the average thorium abundance of 3,883 ppm  $\text{ThO}_2$  calculated from table 16, the deposit contains about 600 tons of  $\text{ThO}_2$ .

#### SCHWARZ RANCH CLAIMS

Several claims, the Honest No. 2 and Honest No. 5, were staked along a radioactive fracture zone and a barite-rich vein, respectively, by Harold Schwarz on his own ranch (pl. 1, fig. 6). The fracture zone is occupied intermittently by quartz vein material and strikes about N. 35° W. and is vertical. It can be traced along strike for about 520 feet and is typically 3 feet wide.

The material from the fracture zone consists of strongly sheared and comminuted country rock to which mineralizing solutions have added quartz, barite, and thorite. Some of the introduced minerals show later fracturing and shearing, indicating postmineralization movement along the structure. Zircon, apatite, and magnetite, present in heavy-mineral separates of fracture zone material, may be original components of the country rock instead of being introduced during the episode of mineralization.

Most of the higher grade parts of this vein have been mined out. Much of this material, however, was still stored on the property at the time of my visit. Some of the highest thorium values in the Wet Mountains area are found in thorite-rich samples collected from the

Schwarz property (table 17). These samples contain 1.9–7.0 percent thorium and average nearly 4 percent. This average is nearly 10 times as large as the average thorium for all samples collected in the Wet Mountains area (table 13). The Schwarz samples have a somewhat higher average  $\Sigma$ LREE content (1.2 times the average  $\Sigma$ LREE in the total samples—table 13) and a much greater  $\Sigma$ HREE content (6.5 times the average  $\Sigma$ HREE in the total samples—table 13). The apparent fractionation of rare-earth elements in the Schwarz samples cannot be explained because no rare-earth minerals were identified. Other than thorium and rare-earth elements, the distribution of elements in the Schwarz samples is not unlike that in other parts of the Wet Mountains area.

The thorium-rich vein appears to extend along strike for 600 feet, exists to a depth of 250 feet, and averages 3 feet thick. The average thorium content is 4 percent. These data yield reserves of 1,500 tons  $\text{ThO}_2$ .

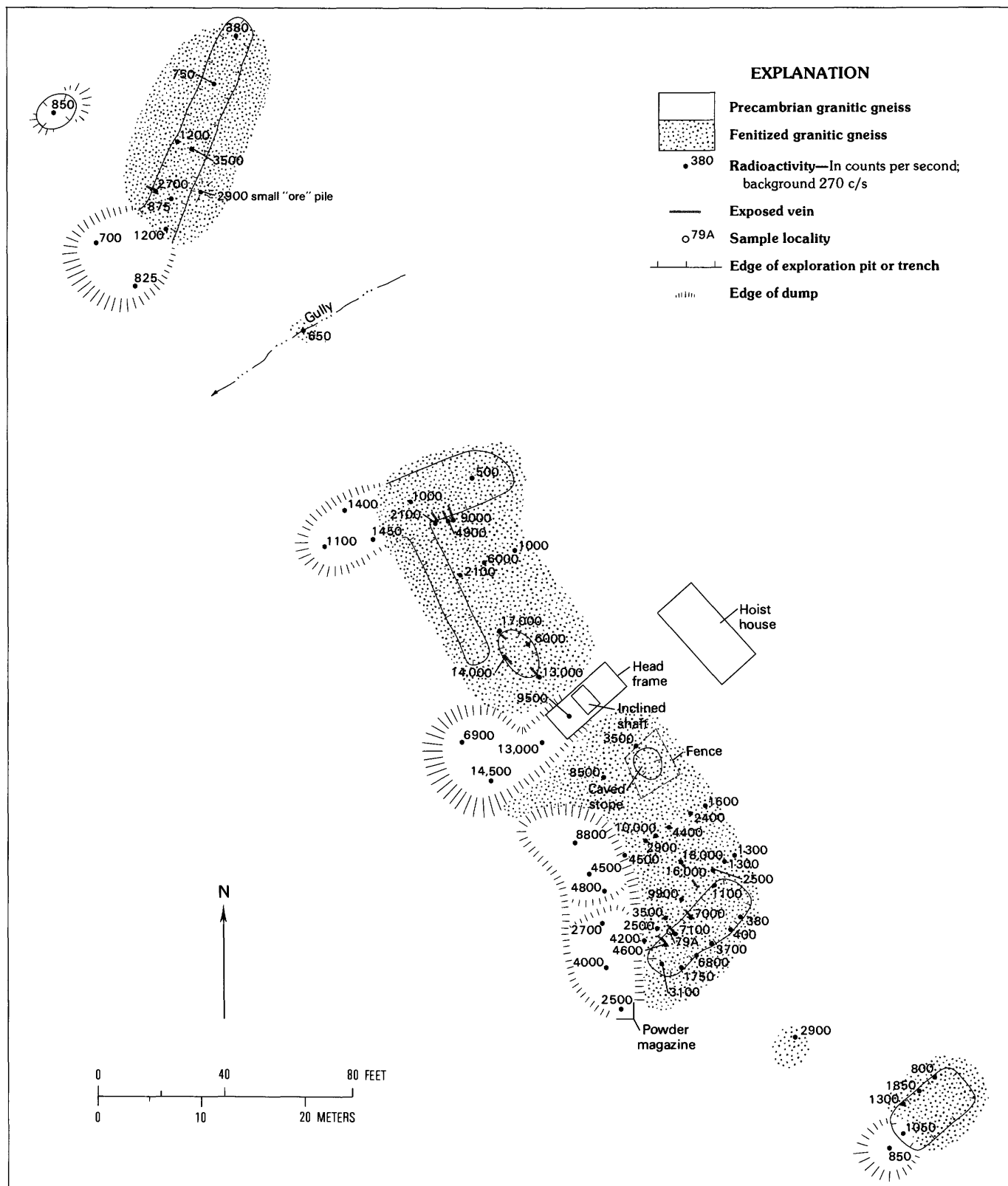
#### GENERAL IKE VEIN

The vein-fracture zone that is covered by the General Ike claim is located near lat 38°12'30" N. and long 105°20' W., but it probably extends along a northwesterly strike for over 4 miles (pl. 1). About 10,300 feet of this structure have been informally designated here as the General Ike vein. The General Ike claim was staked by Lawrence Knobbe along with several partners, but the exact date of the staking is not known.

Samples from along the General Ike vein were collected almost exclusively from small prospect pits. At the sample localities the host rocks are chiefly pink to light-gray, strongly foliated granitic gneisses. The pink color of the gneisses near the vein suggests that they are slightly fenitized. As in most cases, the vein is normal to the foliation in gneisses.

The most abundant minerals in the veins are smoky quartz, potassic feldspar, barite, and several iron oxide minerals, especially goethite and hematite. Other minerals include galena, rutile, and calcite. Much of the radioactivity in the veins and fracture zones is associated with the iron oxides, but X-ray diffractograms of that material do not reveal the presence of any thorium-bearing minerals.

Because of the relatively high barite content, barium is abundant in this vein-fracture zone (table 18). Barium averages about 6.6 percent, over 1 percent more than the average amount in all vein samples (table 13). The lead content also appears to be more abundant than that in other veins. The  $\Sigma$ LREE to  $\Sigma$ HREE ratio of 5.6 is considerably higher than the ratio for all samples, which is 1.5, although the average  $\Sigma$ LREE values are comparable.



Geology by T.J. Armbrustmacher  
and L.M. Osmonson, 1976

FIGURE 5.—Geologic map and sample localities of thorium deposits at the Beardsley deposit, Wet Mountains area, Colorado. Location shown on plate 1.

TABLE 16.—Abundance of selected elements in sample 79A from the Beardsley deposit, Wet Mountains area, Colorado

[Analysis for Th by C.A. Bunker; all other analyses by L.A. Bradley]

Element	Parts per million	Element	Parts per million
Ba.....	1,000	Sr.....	300
Be.....	2	V.....	30
Co.....	5	Y.....	500
Cr.....	30	Zr.....	150
Cu.....	30	Ce.....	300
La.....	150	Ga.....	15
Nb.....	50	Yb.....	50
Ni.....	10	ΣLREE...	1,090
Pb.....	500	ΣHREE...	810
Sc.....	15	Th.....	3,412

The General Ike vein is 10,300 ft long, averages only about 1 ft wide, and persists to about 250 ft in depth. Using the thorium abundance of 2,187 ppm  $\text{ThO}_2$  calculated from table 18, the vein contains about 470 tons  $\text{ThO}_2$ .

### RESOURCES OF THORIUM AND OTHER ELEMENTS

The resources of thorium, rare-earth elements, niobium, and uranium contained in veins and fracture zones and in carbonatite dikes have been reported in Staatz and others (1979) and in Staatz and others (1980), respectively. Data contained in those reports are summarized here.

Total resources are divided into reserves—that is, those resources that are directly measured and

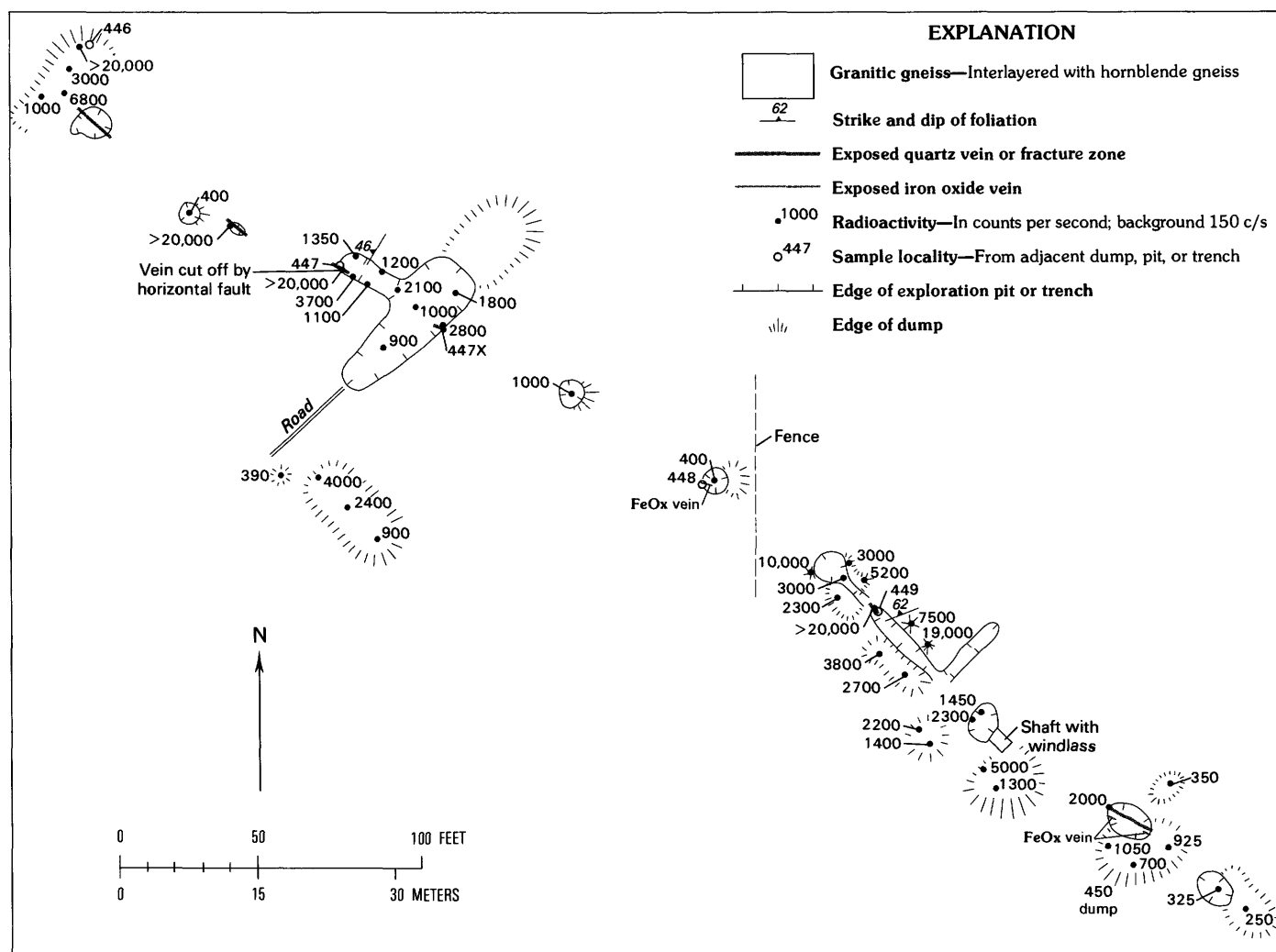


FIGURE 6.—Geologic map and sample localities of thorium deposits at the Schwarz Ranch, Wet Mountains area, Colorado. Location shown on plate 1.

TABLE 17.—*Abundance of selected elements in veins and fracture zones from the Schwarz Ranch claims, Wet Mountains area, Colorado*

[Data given in parts per million. Arithmetic mean calculated from samples 446 to 451, excluding 448 and 452. To calculate arithmetic mean, <30 is replaced by 20, <10 is replaced by 7. Enrichment factor equals arithmetic mean/average igneous rock. Leaders (---) indicate not looked for. Sample localities shown on plate 1 and in figure 6. Analyses for Th by C.M. Bunker and C.A. Bush; all other analyses by L.A. Bradley]

Element	Sample No.						Arithmetic mean	Enrichment factor
	446	447	448	449	451	452		
Ba.....	2,000	3,000	5,000	1,500	20,000	700	6,625	11
Be.....	70	50	10	100	30	7	62	31
Co.....	70	100	30	30	30	20	58	5
Cr.....	300	150	50	15	300	150	191	3
Cu.....	1,000	200	1,000	70	200	150	368	12
La.....	300	700	<30	300	200	150	375	9
Nb.....	200	70	30	<10	200	700	118	6
Ni.....	300	500	500	50	70	30	230	5
Pb.....	1,000	2,000	<10	300	700	50	1,000	67
Sc.....	70	70	15	15	50	20	51	4
Sr.....	700	2,000	70	500	500	200	925	3
V.....	300	150	150	70	300	300	205	2
Y.....	1,000	15,000	70	1,500	1,500	200	4,750	140
Zr.....	300	7,000	15	30	150	150	1,870	12
Ce.....	700	1,500	<10	1,000	700	300	975	13
Ga.....	20	---	---	7	15	30	10	0.6
<sup>1</sup> ELREE...	1,650	3,700	30	2,150	1,200	650	2,175	13
<sup>2</sup> EHREE...	2,070	23,200	70	3,150	2,340	220	7,690	128
Th.....	19,000	70,000	126	50,000	19,500	659	39,625	3,602

<sup>1</sup>Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.

<sup>2</sup>Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

#### SAMPLE DESCRIPTIONS

- 446. Strongly radioactive composite dump sample.
- 447. Thorite-rich, vuggy, FeOx-rich vein material.
- 448. Nonradioactive FeOx-rich vein material.
- 449. Composite sample from 3-foot, radioactive fracture zone.
- 451. Weathered, strongly radioactive fracture zone.
- 452. Maroon-colored clayey gouge from barite vein.

sampled—and into probable potential resources, which are logical extensions of measured reserves both laterally and vertically. Reserves were calculated by multiplying the known length of the vein by average thickness by a depth equal to one-third the length but not exceeding 3,000 feet. A tonnage factor of 12 ft<sup>3</sup>/short ton converts vein volume to vein weight. Vein weight is then multiplied by the average grade of the particular elements. To calculate probable potential resources, the vein was extended along the surface 25 percent of

the known length in each direction unless limited by geologic constraints. The same average width is used and vein depth is calculated the same as for reserves.

Exploration of the veins and fracture zones and carbonatite dikes consisted mainly of shallow prospect pits and dozer cuts, many of which no longer expose bedrock. Samples commonly were collected from these pits or from small dumps if the level of radiation suggested a sufficient thorium content. Because of the lack

TABLE 18.—*Abundance of selected elements in veins and fracture zones in the General Ike vein, Wet Mountains area, Colorado*

[Data given in parts per million. Arithmetic mean calculations: >100,000 is replaced by 150,000; <1 is replaced by 0.7; <10 is replaced by 7; <100 is replaced by 70; <5 is replaced by 3. Enrichment factor equals arithmetic mean/average igneous rock. Leaders (---) indicate not looked for. Sample localities shown on plate 1. Analyses for Th by C.M. Bunker and C.A. Bush; all other analyses by L.A. Bradley]

Element	Sample No.										Arithmetic mean	Enrichment factor
	11	12B	13	14	15	16	17	18	19	21		
Ba.....	>100,000	5,000	70,000	30,000	7,000	>100,000	100,000	70,000	15,000	50,000	65,700	111
Be.....	<1	20	7	15	5	3	3	2	2	15	7	4
Co.....	20	15	20	20	5	50	7	15	5	5	16	1.3
Cr.....	70	30	300	150	70	70	30	30	30	7	79	1.1
Cu.....	50	70	100	70	3	70	150	150	50	30	74	2.5
La.....	1,000	700	200	700	50	150	700	150	150	50	385	9
Nb.....	20	150	500	100	100	20	<10	15	15	<10	93	5
Ni.....	70	70	100	150	30	150	20	20	20	7	64	1.5
Pb.....	15	30	30	15	30	7	15	15	7	5	17	1.2
Sr.....	1,000	200	1,500	700	700	300	300	300	100	100	520	1.8
V.....	50	150	200	50	70	100	50	70	20	7	77	.8
Y.....	70	200	700	70	700	70	150	150	100	50	226	7
Zr.....	30	700	1,500	70	3,000	70	150	70	70	20	568	4
Ce.....	1,500	1,000	500	1,000	<100	200	1,500	200	300	<100	634	8
Ga.....	15	---	15	---	20	---	<5	10	7	<5	10	.6
Yb.....	3	20	70	7	100	7	15	15	10	3	25	7
<sup>1</sup> ΣLREE..	5,100	2,720	1,290	2,870	150	500	3,950	790	720	300	1,839	11
<sup>2</sup> ΣHREE..	73	290	1,040	77	1,010	77	365	215	110	53	331	6
Th.....	3,115	3,090	1,496	2,765	1,482	308	3,566	669	672	2,055	1,922	175

<sup>1</sup>Light rare-earth elements: La, Ce, Pr, Nd, Sm, Eu.

<sup>2</sup>Heavy rare-earth elements: Y, Yb, Gd, Tb, Dy, Ho, Er, Tm, Lu.

## SAMPLE DESCRIPTIONS

11. Dump sample containing barite, specularite, minor sulfides, calcite, and quartz.
- 12B. Fracture zone containing abundant iron oxide.
13. Fracture zone containing abundant iron oxide.
14. Quartz vein containing minor sulfides, iron oxide.
15. Pink feldspar-rich vein containing iron oxide and minor sulfides.
16. Quartz-barite vein containing specularite and minor sulfides.
17. Barite vein containing iron oxide.
18. Fracture zone containing abundant iron oxide.
19. Quartz vein containing abundant iron oxide.
21. Quartz vein containing large euhedral smoky quartz crystals and iron oxide.

of data between prospect pits where the vein or dike is covered, estimates of resources are probably high.

probable potential resources of 4,185 tons Nb<sub>2</sub>O<sub>5</sub>, based on samples containing 0.012 percent Nb<sub>2</sub>O<sub>5</sub>.

## VEINS AND FRACTURE ZONES

The Wet Mountains area contains reserves of 64,200 tons ThO<sub>2</sub> and probable potential resources of 160,500 tons ThO<sub>2</sub> in veins and fracture zones. This estimate is based on a total of 201 samples of veins and fracture zones (localities shown on pl. 1) containing an average of 0.46 percent ThO<sub>2</sub>. The Wet Mountains area also contains reserves of 29,300 tons ΣLREE and probable potential resources of 73,270 tons ΣLREE, as well as reserves of 19,540 tons ΣHREE and probable potential resources of 48,850 tons ΣHREE. This estimate is based on samples containing an average of 0.21 percent ΣLREE and 0.14 percent ΣHREE. The Wet Mountains area contains reserves of 1,675 tons Nb<sub>2</sub>O<sub>5</sub> and

## CARBONATITE DIKES

A total of 52 samples of primary magmatic carbonatite were collected in the Wet Mountains area. Because many of the carbonatites tend to be elongated, lens-shaped bodies that have a limited strike length, resources were calculated only on the seven largest carbonatite dikes. The seven largest dikes have the following average grades and resources: 0.17 percent ThO<sub>2</sub>, reserves of 131 tons ThO<sub>2</sub>, and probable potential resources of 753 tons ThO<sub>2</sub>; 0.0097 percent Nb<sub>2</sub>O<sub>5</sub>, reserves of 40 tons Nb<sub>2</sub>O<sub>5</sub>, and probable potential resources of 228 tons; 0.0031 percent U<sub>3</sub>O<sub>8</sub>, reserves of 17 tons U<sub>3</sub>O<sub>8</sub>, and probable potential resources of 105 tons; 2.15 percent total rare-earth oxides, reserves of

2,500 tons total rare-earth oxides, and probable potential resources of 14,300 tons.

## REFERENCES CITED

- Armbrustmacher, T. J., 1975, Thorium deposits in the Wet Mountains area, Fremont and Custer Counties, Colorado, in Craig, L. C., Brooks, R. A., and Patton, P. C., eds., Abstracts of the 1975 Uranium and Thorium Research and Resources Conference: U.S. Geological Survey Open-File Report 75-595, p. 4.
- , 1976, Thorium deposits in the Wet Mountains area, Fremont and Custer Counties, Colorado: U.S. Geological Survey Open-File Report 76-284, 18 p.
- , 1979, Replacement and primary magmatic carbonatites from the Wet Mountains area, Fremont and Custer Counties, Colorado: *Economic Geology*, v. 74, no. 4, p. 888-901.
- , 1981, Geologic occurrence and resource potential of thorium in the Wet Mountains area, Custer and Fremont Counties, Colorado—An update: Geological Society of America Abstracts and Programs, v. 13, no. 4, p. 190.
- , 1984, Alkaline rock complexes in the Wet Mountains area, Custer and Fremont Counties, Colorado: U.S. Geological Survey Professional Paper 1269, 33 p.
- Armbrustmacher, T. J., and Brownfield, I. K., 1978, Carbonatites in the Wet Mountains area, Custer and Fremont Counties, Colorado—Chemical and mineralogical data: U.S. Geological Survey Open-File Report 78-177, 6 p.
- Armbrustmacher, T. J., Brownfield, I. K., and Osmonson, L. M., 1979, Multiple carbonatite dike at McClure Gulch, Wet Mountains alkalic province, Fremont County, Colorado: *Mountain Geologist*, v. 16, no. 2, p. 37-45.
- Armbrustmacher, T. J., and Hedge, C. E., 1982, Genetic implications of minor-element and Sr-isotope geochemistry of alkaline rock complexes in the Wet Mountains area, Fremont and Custer Counties, Colorado: *Contributions to Mineralogy and Petrology*, v. 79, p. 424-435.
- Armbrustmacher, T. J., Hedge, C. E., and Parker, R. L., 1979, Alkaline rock complexes in the Wet Mountains area, Fremont and Custer Counties, Colorado—Genetic implications of minor-element and Sr-isotope geochemistry: Geological Society of America Abstracts with Programs, v. 11, no. 7, p. 266.
- Blattner, Peter, and Cooper, A. F., 1974, Carbon and oxygen isotopic composition of carbonatite dikes and metamorphic country rock of the Haast Schist terrain, New Zealand: *Contributions to Mineralogy and Petrology*, v. 44, no. 1, p. 17-27.
- Boyer, R. E., 1962, Petrology and structure of the southern Wet Mountains, Colorado: Geological Society of America Bulletin, v. 73, no. 9, p. 1047-1070.
- Brock, M. R., and Singewald, Q. D., 1968, Geologic map of the Mount Tyndall quadrangle, Custer County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-596, scale 1:24,000.
- Christman, R. A., Brock, M. R., Pearson, R. C., and Singewald, Q. D., 1954, Wet Mountains, Colorado, thorium investigations, 1952-1954: U.S. Geological Survey Trace Elements Investigation Report 354, 52 p.
- , 1959, Geology and thorium deposits of the Wet Mountains, Colorado—A progress report: U.S. Geological Survey Bulletin 1072-H, p. 491-535.
- Christman, R. A., Heyman, A. M., Dellwig, L. F., and Gott, G. B., 1953, Thorium investigations 1950-52, Wet Mountains, Colorado: U.S. Geological Survey Circular 290, 40 p.
- Cross, Whitman, 1896, Geology of Silver Cliff and the Rosita Hills, Colorado: U.S. Geological Survey 17th Annual Report, pt. 2, p. 263-403.
- Deines, Peter, and Gold, D. P., 1973, The isotopic composition of carbonatite and kimberlite carbonates and their bearing on the isotopic composition of deep-seated carbon: *Geochimica et Cosmochimica Acta*, v. 37, no. 7, p. 1709-1733.
- Dellwig, L. F., 1951, Preliminary summary report on the Wet Mountains thorium area, Custer and Fremont Counties, Colorado: U.S. Geological Survey Trace Elements Memorandum Report 287, 14 p.
- Eckel, E. B., 1961, Minerals of Colorado—A 100-year record: U.S. Geological Survey Bulletin 1114, 399 p.
- Emmons, S. F., 1896, The mines of Custer County, Colorado: U.S. Geological Survey 17th Annual Report, pt. 2, p. 405-472.
- Fisher, F. G., and Meyrowitz, Robert, 1962, Brockite, a new calcium thorium phosphate from the Wet Mountains, Colorado: *American Mineralogist*, v. 47, p. 1346-1355.
- Gold, D. P., 1963, Average chemical composition of carbonatites: *Economic Geology*, v. 58, no. 6, p. 988-991.
- Goles, G. G., 1967, Trace elements in ultramafic rocks, p. 352-362, in Wyllie, P. J., ed., *Ultramafic and related rocks*: New York, John Wiley, 464 p.
- Graf, D. L., 1960a, Geochemistry of carbonate sediments and sedimentary carbonate rocks—Part III, Minor element distribution: Illinois State Geological Survey Division Circular 301, 71 p.
- , 1960b, Geochemistry of carbonate sediments and sedimentary carbonate rocks—Part IV—A, Isotopic composition-chemical analyses: Illinois State Geological Survey Division Circular 308, 42 p.
- Heinrich, E. W., 1965, The Goldie carbonatite, Fremont County, Colorado—A unique cryolite occurrence [abs.]: Geological Society of America Special Paper 87, p. 389.
- , 1966, The geology of carbonatites: Chicago, Rand McNally, 555 p.
- , 1977, Aluminofluoride minerals of the Goldie carbonatite, Fremont County, Colorado: *Mountain Geologist*, v. 14, p. 33-46.
- Heinrich, E. W., and Anderson, R. J., 1965, Carbonatites and alkalic rocks of the Arkansas River area, Fremont County, Colorado, pt. 2, Fetic gas from carbonatite and related rocks: *American Mineralogist*, v. 50, nos. 11-12, p. 1914-1920.
- Heinrich, E. W., and Dahlem, D. H., 1966, Carbonatites and alkalic rocks of the Arkansas River area, Fremont County, Colorado: *Mineralogical Society of India, IMA Volume*, Naidu, P. R. J., ed., p. 37-44.
- , 1969, Dikes of the McClure Mountain-Iron Mountain alkalic complex, Fremont County, Colorado, U.S.A.: *Bulletin Volcanologique*, v. 33, p. 960-976.
- Heinrich, E. W., and Moore, D. G., Jr., 1970, Metasomatic potash feldspar rocks associated with igneous alkalic complexes: *Canadian Mineralogist*, v. 10, pt. 3, p. 571-584.
- Heinrich, E. W., and Quon, S. H., 1963, New type of deposit of aluminofluoride minerals from Fremont County, Colorado [abs.]: Geological Society of America Special Paper 73, p. 169.
- Heinrich, E. W., and Shappirio, J. R., 1966, Alkali rocks and carbonatites of the Arkansas River canyon, Fremont County, Colorado, pt. 3—The Amethyst carbonatites: *American Mineralogist*, v. 51, no. 7, p. 1088-1106.
- Langmuir, Donald, and Herman, J. S., 1980, The mobility of thorium in natural waters at low temperatures: *Geochimica et Cosmochimica Acta*, v. 44, p. 1753-1766.
- Mariano, A. N., 1979, Enhancement and classification of fentization by cathodoluminescence: Geological Association of Canada—Mineralogical Association of Canada Program with Abstracts, v. 4, p. 65.
- Moore, D. G., Jr., 1969, Geology, mineralogy, and origin of feldspar rocks associated with alkalic carbonatitic complexes, northern Wet

- Mountains, Colorado: Ann Arbor, University of Michigan Ph. D. dissertation, 182 p.
- Olson, J. C., Marvin, R. F., Parker, R. L., and Mehnert, H. H., 1977, Age and tectonic setting of lower Paleozoic alkalic and mafic rocks, carbonatites, and thorium veins in south-central Colorado: U.S. Geological Survey Journal of Research, v. 5, no. 6, p. 673-687.
- Papson, R. P., 1981, Mineralogy and geochemistry of carbonatites from the Gem Park Complex, Fremont and Custer Counties, Colorado: Fort Collins, Colorado State University M.S. thesis, 72 p.
- Parker, R. L., and Hildebrand, F. A., 1963, Preliminary report on alkalic intrusive rocks in the northern Wet Mountains, Colorado, in Geological Survey research 1962: U.S. Geological Survey Professional Paper 450-E, p. E8-E10.
- Parker, R. L., and Sharp, W. N., 1970, Mafic-ultramafic rocks and associated carbonatites of the Gem Park Complex, Custer and Fremont Counties, Colorado: U.S. Geological Survey Professional Paper 649, 24 p.
- Rye, R. O., and Ohmoto, Hiroshi, 1974, Sulfur and carbon isotopes and ore genesis—A review: Economic Geology, v. 69, no. 6, p. 826-842.
- Scott, G. R., and Taylor, R. B., 1975, Post-Paleocene Tertiary rocks and Quaternary volcanic ash of the Wet Mountain Valley, Colorado: U.S. Geological Survey Professional Paper 868, 15 p.
- Scott, G. R., Taylor, R. B., Epis, R. C., and Wobus, R. A., 1976, Geologic map of the Pueblo 1°×2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-775.
- Sharp, W. N., 1978, Geologic map of the Silver Cliff and Rosita volcanic centers, Custer County, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1081, scale 1:24,000.
- Shawe, D. R., and Parker, R. L., 1967, Mafic-ultramafic layered intrusion at Iron Mountain, Fremont County, Colorado: U.S. Geological Survey Bulletin 1251-A, p. A1-A28.
- Sheppard, S.M. F., and Dawson, J. B., 1973,  $^{13}\text{C}/^{12}\text{C}$  and D/H isotope variations in "primary igneous carbonatites": Fortschritte der Mineralogie, v. 50, p. 128-129.
- Singewald, Q. D., and Brock, M. R., 1956, Thorium deposits in the Wet Mountains, Colorado: U.S. Geological Survey Professional Paper 300, p. 581-585.
- Singewald, Q. D., Christman, R. A., Brock, M. R., Swinney, C. M., Pearson, R. C., Calkins, J. A., and Heyman, A. M., 1955, Geologic and radiometric maps of the McKinley Mountain area, Wet Mountains, Colorado: U.S. Geological Survey Mineral Investigations Field Studies Map MF-37, 4 sheets.
- Staatz, M. H., 1974, Thorium veins in the United States: Economic Geology, v. 69, no. 4, p. 494-507.
- Staatz, M. H., Armbrustmacher, T. J., Olson, J. C., Brownfield, I. K., Brock, M. R., Lemons, J. F., Jr., Coppa, L. V., and Clingan, B. V., 1979, Principal thorium resources in the United States: U.S. Geological Survey Circular 805, 42 p.
- Staatz, M. H., Hall, R. B., Macke, D. L., Armbrustmacher, T. J., and Brownfield, I. K., 1980, Thorium resources of selected regions in the United States: U.S. Geological Survey Circular 824, 32 p.
- Taylor, H. P., Jr., 1974, The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition, in Stable isotopes as applied to problems of ore deposits: Economic Geology, v. 69, no. 6, p. 843-883.
- Taylor, H. P., Jr., Frechen, Josef, and Degens, E. T., 1967, Oxygen and carbon isotope studies of carbonatites from the Laacher See district, West Germany and the Alnö district, Sweden: Geochimica et Cosmochimica Acta, v. 31, p. 407-430.
- Taylor, R. B., 1974, Reconnaissance geologic map of the Deer Peak quadrangle and southern part of the Hardscrabble Mountain quadrangle, Custer and Huerfano Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-870.
- Taylor, R. B., Scott, G. R., Wobus, R. A., and Epis, R. C., 1975a, Reconnaissance geologic map of the Cotopaxi 15-minute quadrangle, Fremont and Custer Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-900.
- , 1975b, Reconnaissance geologic map of the Royal Gorge quadrangle, Fremont and Custer Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-869.
- Tweto, Ogden, 1987, Rock units of the Precambrian basement in Colorado: U.S. Geological Survey Professional Paper 1321-A, 54 p.
- Wedepohl, K. E., 1971, Geochemistry: New York, Holt, Rinehart, and Winston, 231 p.





